Longitudinal changes in force production of young competitive swimmers: assessment tools for training control and optimization

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Declaração de Integridade

Eu, Catarina Maria Simões da Costa Santos, que abaixo assino, estudante com o número de inscrição D2541 do Doutoramento em Ciências do Desporto da Faculdade de Ciências Sociais e Humanas, declaro ter desenvolvido o presente trabalho e elaborado o presente texto em total consonância com o **Código de Integridades da Universidade da Beira Interior**.

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CHAVE MÓVEL

Dedicated to my lovely mom and Oliveira...

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List of Publications

This Doctoral Thesis was supported by the research articles shown in Table 1.

Table 1. Identification of peer reviewed articles, indexing, and metrics.

Year	Reference	IF JCR
2021	Santos, C. C., Marinho, D. A., Neiva, H. P., & Costa, M. J. (2021). Propulsive forces in human competitive swimming: a systematic review on direct assessment methods. *Sports Biomechanics*. Advance online publication.	2.896
2022	Santos, C. C., Marinho, D. A., & Costa, M. J. (2022). The mechanical and efficiency constraints when swimming front crawl with the Aquanex System. *Journal of Human Kinetics*, 84, 166-173.	2.193
2022	Santos, C. C., Marinho, D. A., & Costa, M. J. (2022). Reliability of using a pressure sensor system to measure in-water force in young competitive swimmers. *Frontiers in Bioengineering and Biotechnology*, 10, 903753.	6.064
UR	Santos, C. C., Costa, M .J., Forte, P., & Marinho, D. A. (under review). A comparison of tethered swimming and pressure sensors to measure in-water force in young competitive swimmers. *Journal of Biomechanics*.	2.789
UR	Santos., C. C., Marinho, D. A., & Costa., M. J. (under review). Within-season changes in young swimmers in-water force, performance, kinematics, and anthropometrics. *Journal of Sports Sciences*.	3.943
2023	Santos., C. C., Costa., M. J., & Marinho, D. A. (2023). The effects of 6-week training cessation on anthropometrics, in-water Force, performance, and kinematics of young competitive swimmers: a maturity development approach. *International Journal of Sports Physiology and Performance*. Ahead of Print.	4.211

IF, impact factor; JCR, journal citation reports; UR, under review.

In addition, Table 2 shows the preliminary studies according to the type of scientific dissemination.

Table 2. Identification of peer reviewed abstracts, scientific events, and awards.

Year	Reference	Type
2022	Santos, C. C., Costa, M. J., Paiva, D., Rodrigues, P., & Marinho, D. A. (2022). The effect of using a parachute on the propulsive force and stroke mechanics during pace-controlled swimming: a case study with an international level swimmer. Atas do 44º Congresso Técnico Científico da Associação Portuguesa de Técnicos de Natação. *Motricidade*, 18(S1), 16-17.	OC*
2022	Santos, C. C., Marinho, D. A., & Costa, M. J. (2022). How much strength the young competitive swimmers are able to transfer from dry land to water? A pilot study. In Dela, F., Piacentini, M.F., Helge, J.W., Lluch, Á., Sáez, E., Blanco, F., Tsolakidis, E., Ruiter, C.J., & Tsolakidis, E. (eds). B*ook of Abstracts from the 27th Annual Congress of the European College of Sport Science*. p. 265.	OC

Table 2. *(continued)*

Year	Reference	Type
2022	Santos., C. C., Costa., M. J., Marinho, D. A., Barbosa, T. M., & Rosa, S. M. (accepted). Validation of a differential pressure system to assess in-water forces in competitive swimming. Proceedings of the 13th World Congress of Performance Analysis of Sport & 13th International Symposium on Computer Science in Sport. *Advances in Intelligent Systems and Computing*.	OC
2022	Santos., C. C., Marinho, D. A., Campos, T., Pinto, M., & Costa, M. J. (accepted). Follow-up of young swimmers' kinematics and kinetics during the winter season macrocycle. Atas do 45º Congresso Técnico Científico da Associação Portuguesa de Técnicos de Natação. *Motricidade*.	OC**
2023	Santos, C. C., Marinho, D. A., & Costa, M. J. (accepted). Changes in force and symmetry of young swimmers over a full competitive season and training cessation. *XIVth International Symposium on Biomechanics and Medicine in Swimming*. University of Leipzig, Germany	OC
2021	Santos, C.C. (2021). Nuevas Tecnologías Aplicadas a la Evaluación de la Fuerza Propulsiva en Natación. *IV Congreso Internacional de Ciencias Aplicadas a la Natación*. Escuela de Educación Física y Deporte, Universidad de Costa Rica (online).	K

OC, oral communication; K, keynote; *, award - best oral communication (2nd place); **, award - best oral communication (1st place).

Abstract

The general purpose of this thesis was to analyze the changes in force production of young competitive swimmers during a full competitive season and over a detraining period. Simultaneously, there was an attempt to understand if a two-hand pressure system is a suitable tool to be used for monitoring in-water forces in swimmers from this age cohort. To support this, specific purposes were defined according to the following sequence: (i) to systematically review the available literature focusing on the human propulsive forces in swimming; (ii) to verify the reliability of a pressure sensors system; (iii) to understand if the system impairs the swimming mechanics and efficiency; (iv) to perform an agreement between available methods that measure in-water forces; (v) to determine the changes in force production of young swimmers during a competitive season; (vi) to understand how a detraining period affects in-water forces according to different maturity status. Main results suggest that: (i) there is a scarce number of studies dealing with long-term changes in-water forces of young swimmers, and the methods used for that purpose were little explored; (ii) a two-hand pressure sensors system showed to be reliable to measure in-water forces during front-crawl swimming; (iii) the system did not induced any mechanical or efficiency constraints; (iv) a correction factor is needed to compare the in-water forces obtained by different methods; (v) a full competitive season seems to promote improvements in force production along with an increase in asymmetric motion; and (vi) in-water forces seems to remain unchanged even with a six-weeks of training cessation.

Keywords

Swimming; front-crawl; in-water forces; pressure sensors; tethered-swimming; testing

Resumo

A presente tese objetivou analisar as alterações na produção da força ao longo de uma época competitiva e destreino em nadadores jovens. Simultaneamente, houve uma tentativa de compreender se um sistema de sensores de pressão para as mãos é uma ferramenta adequada para monitorizar as forças na água em nadadores desta faixa etária. Para tal, foram definidos objetivos específicos de acordo com a seguinte sequência: (i) rever sistematicamente a literatura disponível nas forças propulsivas humanas na natação; (ii) verificar a fiabilidade de um sistema de sensores de pressão; (iii) compreender se o sistema afeta a mecânica e eficiência do nado; (iv) realizar uma concordância entre os métodos disponíveis que medem as forças na água; (v) determinar as alterações na produção de força dos jovens nadadores durante uma época competitiva; e (vi) compreender de que forma um período de destreino afeta as forças na água de acordo com distintos estados de maturação. Os principais resultados sugerem que: (i) existe um número escasso de estudos que analisam as alterações a longo prazo das forças na água de jovens nadadores, e os métodos utilizados para esse fim foram pouco explorados; (ii) o sistema de sensores de pressão para as mãos mostrou ser fiável para medir as forças na água durante o nado de crol; (iii) o sistema não induziu quaisquer restrições mecânicas ou de eficiência; (iv) é necessário um fator de correção para comparar as forças na água obtidas por diferentes métodos; (v) uma época competitiva parece promover melhorias na produção de força juntamente com um aumento de um movimento assimétrico; e (vi) as forças na água parecem permanecer inalteradas mesmo com uma interrupção de seis semanas de treino.

Palavras-chave

Natação; crol; forças na água; sensores de pressão; nado amarrado; avaliações

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List of abbreviations

BMI	Body mass index
CA	Chronological age
CFD	Computational fluid dynamics
D	Dominant
F_{PEAK}	Mean peak force
F_{MEAN}	Mean force
HSA	Hand surface area
l	Arm length
LTAD	Long-term athlete development
M_i	Moments
MO	Maturity offset
ND	Non-dominant
PF	Propulsive force
PF_{PEAK}	Propulsive peak force
PF_{MEAN}	Propulsive mean force
PHV	Peak heigh velocity
PS	Pressure sensors
QI	Quality Index
RF_{PEAK}	Peak resultant force
RF_{MEAN}	Mean resultant force
SF_{PEAK}	Subsequent peak force
SI	Stroke index
SL	Stroke length
SR	Stroke rate
SyI	Symmetry index
T1	Trial 1
T2	Trial 2
T25	Time of 25m
TS	Tethered-swimming
v25	Velocity of 25m
v	Velocity
ηp	Arm stroke efficiency

Chapter 1. General Introduction

Swimming research has increased over the years, standing out at the beginning of the series "International Symposium on Biomechanics and Medicine in Swimming" in the 1970s (Barbosa et al., 2021). For instance, studies from 2013 up to 2017 focus on swimming topic represented 6% of the total number of studies in sport sciences (Costa & Barbosa, 2018).

Within this, swimming stands out as a cyclic sport of great interest that deserves to be deeply studied. Competitive swimming from childhood to adulthood aims to accomplish a given distance in the shortest time (Costa et al., 2012). In the last couple of decades, basic and/or field-oriented research within this sport has been mainly focused on biomechanics and physiology domains, but a trend for applying a more interdisciplinary assessment has grown in interest (Barbosa, Pinto et al., 2010). Still, most of the available literature derives from studies that used adult swimmers as subjects, as at younger ages some ethical issues could arise from the experiments (Barbosa, Costa et al., 2010).

Talent identification and development programs rely on identifying and understanding changes in key-factors of performance within and between competitive seasons. Since young swimmers go through a growth and biological maturation process, long-term athlete development (LTAD) models aim to provide them the fundamental motor skills (Lang & Light, 2010). From the available models, it seems acceptable and useful that coaches can follow that reasoning in their daily practice (e.g., Costa et al., 2021). This assumption includes testing swimmers at so early ages and giving them support for a more harmless development through their careers. So, a deeper knowledge and understanding about deterministic models that gather an interdisciplinary approach should be considered. The early model proposed for competitive swimming (Barbosa, Bragada et al., 2010) highlighted an interplay between anthropometrics and kinematics, and how those links would influence energetics, and then swimming performance. Still, the model grew (i.e., updated) and new domains, such as dry-land strength & conditioning and in-water kinetics, were included to accomplish a deeper holistic interpretation (Barbosa et al., 2013).

Swimmers' capacity to move through the water depends on the amount of applied in-water force and on the drag forces opposed to the forward motion (Barbosa et al., 2020). Despite the complexity of the aquatic environment (i.e., water properties), some progress was made to understand the kinetics domain. In-water forces have been estimated through direct and indirect methods, namely by inverse dynamics (estimations; Deschodt et al., 1999), measurement of active drag system (MAD system; Formosa et al., 2012), computational fluid dynamics (CFD, i.e., numerical simulations; Marinho et al., 2010), tethered (Magel et al., 1970) or semi-tethered (Cuenca-Fernández et al., 2020) swimming, and pressure sensors systems (Takagi & Wilson, 1999). However, in-water assessments should mimic as much as possible the movement pattern of the body limbs leading to a more ecological environment (Barbosa et al., 2020). Although some previous systematic reviews were carried-out on indirect methods (Andersen & Sanders, 2018; Gomes & Loss, 2015; Takagi et al., 2015), the available literature on direct methods has not yet been gathered. This may help to get a deeper understanding of methods that allows retrieved force data in a more similar condition than free-swimming (Study 1). Plus, providing comparable data with different methods becomes extremely useful (Study 2), as the availability or costs of different tools might impair training monitoring or data comparison between different swimming squads (Mooney et al., 2016).

A circumstantial prevalence of total forces (propulsive or resistive), or an increased or decreased added mass effect during a given swim stroke cycle leads to a given swimming velocity (Vilas-Boas et al., 2010). As the ability to apply force in the water could be a key-factor in swimmers' forward displacement, the search for accurate and reliable data should be the ultimate goal of field-oriented research (Study 3). Data from the individual force-time curve enables to assess several parameters such as the peak and mean in-water force (Amaro et al., 2017). It is noteworthy that an increment in these forces leads to an enhancement in the swimming performance mostly at a sprint pace (Gatta et al., 2016; Toussaint & Truijens, 2005). Although such parameters have been assessed with some reliable methods (Amaro et al., 2014), mechanical constraints may arise due to the "nature" of the assessments. For instance, if swimmers are assessed without forward displacement some concerns may raise up in the water flow (Soncin et al., 2017) and stroke pattern (Psycharakis et al., 2011). The constraints imposed by several devices during swimming assessments are already a topic of interest and slight changes in the biomechanical pattern have been reported while specific equipment's were used for physiological assessment (e.g., Barbosa, Silva et al., 2010; Conceição et al., 2013). However, to date, the impairments on swimmers' stroke pattern promoted by any system that allowed to retrieve in-water forces have never been attempted (Study 4).

Research in competitive swimming was mainly developed with cross-sectional experimental designs (Costa et al., 2010). This type of design is limited to a single assessment point (Costa et al., 2015) and does not provide cues about the cause-effect relationship over time (Ferreira et al., 2016). Although cross-sectional studies give some clues about forces behavior by establishing relationships or comparing cohorts (Morouço et al., 2014), a research gap still remains when considering long-term approaches. Monitoring the short or long-term changes provides fundamental insights into the performance improvements and the training effectiveness (Costa et al., 2010). Young swimmers' performance is characterized by a multifactorial and dynamic phenomenon, where anthropometrics and biomechanical characteristics (kinematics or hydrodynamics) define the energetic profile and can contribute to performance enhancement (Morais et al., 2021). For instance, parameters within the biomechanics domain seem to contribute approximately 50-60% to young swimmers' performance (Morais et al., 2012). However, growth spurts at such early ages often occur during (Abbott et al., 2021) or off the season (Moreira et al., 2014). So, several performance-related parameters are expected to change over time mainly due to the growth and biological maturation processes. The few available longitudinal studies with young swimmers strongly considered the anthropometric, energetic, kinematics, efficiency, or dry-land strength/power (Batalha et al., 2013; Batalha et al., 2014; Fiori et al., 2022; Garrido et al., 2010; Morais et al., 2013; Zacca et al., 2020) changes over different moments in time. Nevertheless, to the best of our knowledge, no study has tested how in-water forces were modified by training and if (non) linear fluctuations may exist during a competitive season (Study 5) and training cessation (Study 6).

In this sense, there was here a chance to explore the importance of in-water forces to the enhancement of swimming performance, by conducting a deeper analysis on the effects of training/detraining at early ages. A secondary aim was to provide a use-to-use and friendly method that can help coaches to monitor in-water forces for daily basis, and to properly define the annual training periodization according to the swimmer's response. Thus, the present thesis aimed to analyze the changes in force production during a full competitive season and over a detraining period. Simultaneously, there was an attempt to understand if a two-hand pressure system is a suitable tool to be used for monitoring force adaptations in young swimmers.

This thesis was developed according to the following sequence:

- Chapter 2 presents a systematic review based on the available literature about human propulsive forces in competitive swimming retrieved with direct assessment methods:
    - Study 1. Propulsive forces in human competitive swimming: a systematic review on direct assessment methods.
- Chapter 3 displays the experimental studies conducted in the assessment tools:

  - Study 2. A comparison of tethered swimming and pressure sensors to measure in-water force in young competitive swimmers.
  - Study 3. Reliability of using a pressure sensor system to measure in-water force in young competitive swimmers.
  - Study 4. The mechanical and efficiency constraints when swimming front crawl with the Aquanex System.
- Chapter 4 displays the experimental studies conducted in longitudinal approaches:
  - Study 5. Within-season changes in young swimmers in-water force, performance, kinematics, and anthropometrics.
  - Study 6. The effects of six-week training cessation on anthropometrics, in-water force, performance, and kinematics of young competitive swimmers: a maturity development approach.

Then, a general discussion of the results followed by the main conclusions of the presented thesis are obtained on the six studies performed (Chapter 5). Suggestions for future research are also presented (Chapter 6). In addition, pilot and supplementary studies are displayed in Appendices I-V.

Chapter 2. Literature review

Study 1. Propulsive forces in human competitive swimming: a systematic review on direct assessment methods

Abstract

Human propulsive forces are a key-factor to enhance swimming performance, but there is scarce knowledge when using direct assessments. The aim of this review was to analyze the evidence about human propulsive forces in competitive swimming measured by direct assessment methods. A search up to 30 June 2020 was performed in Web of Science, PubMed, and Scopus databases. The Downs and Black Quality Assessment Checklist was used to assess the quality index (QI) of the included studies. Out of 2530 screened records, 35 articles met the inclusion criteria. Tethered-swimming and differential pressure sensors allow directly measure propulsive forces. Cross-sectional designs measured peak and mean propulsive force during the front crawl stroke and including men/boys (≥15 years-old) at different competitive levels were mostly reported. Men are more able to show higher propulsive forces than women counterparts. Short- and long-term effects were observed while using dry-land and in-water training programmes. The magnitude of propulsive force is dependent on the type of assessment method, swimming stroke, number of body limbs and gender. While the short-term effects supporting the different training programmes lead to an increase in propulsive force, there is a lack of long-term evidence.

Key words: swimming strokes; direct; methods; gender; segmental; actions; training

Santos, C. C., Marinho, D. A., Neiva, H. P., & Costa, M. J. (2021). Propulsive forces in human competitive swimming: a systematic review on direct assessment methods. *Sports Biomechanics*. Advance online publication.

Introduction

The human locomotion in water results from the interaction of propelling limbs with the fluid. Swimmers' capacity to move through the water depends on the amount of applied propulsive force and on the drag forces opposed to a forward motion. Human propulsive forces are generated by the upper- and lower-limbs resulting from arm-pulling and leg-kicking coordinated actions (Cortesi et al., 2019). It has been suggested that the arm-pulling represents 85% to 90% of the overall propulsion in front crawl (T. M. Barbosa et al., 2020; Deschodt et al., 1999), but the kicking action should not be discarded (T. M. Barbosa et al., 2011; Ng et al., 2020).

The assessment of propulsive forces in competitive swimming is a key-aspect for training control and diagnosis. The quantification of the force output may help to define singular aspects of the stroke (i.e., most propulsive phases), identifying imbalances between both sides of the body or establishing some links with key kinematic variables (Morouço, Marinho, Fernandes et al., 2015; Psycharakis et al., 2011). However, the complexity of the aquatic environment hampers the assessment of these forces (Morouço, Keskinen et al., 2011). Still, some progress was made in the past years on how forces are measured, and the kind of used methods for that purpose. The literature on this topic reports the use of indirect/direct methods with humans or robotic models (T. M. Barbosa et al., 2020; Cohen et al., 2017; Kudo et al., 2013; Marinho et al., 2010; Morouço, Keskinen et al., 2011; Morouço, Marinho, Fernandes et al., 2015; Ng et al., 2020; Psycharakis et al., 2011; Samson et al., 2018; Tsunokawa et al., 2018). Tethered-swimming (e.g., with a load-cell) is one of the direct methods often used to measure propulsive forces directly (Morouço, Keskinen et al., 2011), while computational fluid dynamics (CFD; i.e., numerical simulations) (Cohen et al., 2017; Marinho et al., 2010) or inverse dynamics (estimations) based on kinematic parameters are reported to the indirect assessment under steady and unsteady conditions (Cohen et al., 2017; Deschodt et al., 1999). However, most studies showed propulsive forces data using indirect methods in human mechanisms (Samson et al., 2018). Here the ecological validity remains somehow limited, even though these methods provide valuable insights on the swimming propulsion (T. M. Barbosa et al., 2020), and some of those might not be the most suitable because: (i) instruments/software are extremely expensive; (ii) at some point they constrain the swimmer's technique; and (iii) they do not provide real-time analytical data. So, the use of direct methods is a tech-point aspect allowing to get swift and real-time feedback to help swimming coaches tracking-down propulsive force data, as well as the force deficits. Furthermore, they provide an approach that mimics as much as possible the movement pattern of the body limbs leading to a more ecologically valid environment (T. M. Barbosa et al., 2020).

The individual force–time curve enables to assess several parameters such as the propulsive peak force (PF_{PEAK}) and the propulsive mean force (PF_{MEAN}). The increment of those forces leads to an enhancement in the performance outcome mostly at a sprinting pace (Gatta et al., 2016; Toussaint & Truijens, 2005). There is clear evidence showing meaningful associations between PF_{PEAK} and velocity at 50-m (Morouço et al., 2014), 100-m (Rozi et al., 2018) and 200-m (K. B. Dos Santos et al., 2017), as well as between PF_{MEAN} and velocity at 50-m (Loturco et al., 2015) and 100-m (Morouço et al., 2012). Less clear is the pattern of forces when comparing competitive swimming strokes (Morouço, Keskinen et al., 2011) segmental actions (Yeater et al., 1981) or swimmers' characteristics (Silva et al., 2019). In fact, previous systematic reviews on the topic were carried-out on indirect methods (e.g., numerical simulations and particle image velocimetry) in a specific segmental action (e.g., flutter kick) (Andersen & Sanders, 2018; Gomes & Loss, 2015; Takagi et al., 2015).

With this in mind, the purpose of this review was to summarise and analyse the state of the art about human propulsive forces in competitive swimming based on the studies that retrieved the data using direct assessment methods. Here, there is an opportunity to fill the state of the art highlighting the studies that showed propulsive forces using direct methods. This will help both coaches and researchers to be more precise when planning training sets or defining proper assessments to develop propulsive forces from their competitors.

Methods

Search strategy

A systematic review was conducted according to PRISMA (Preferred Reporting Items for Systematic reviews and Meta-analyses) guidelines (Moher et al., 2009) and registered in the International Prospective Register of Systematic Reviews (PROSPERO) under the code CRD42020200398. A comprehensive and extensive search of original articles published between 1 January 1980 and 30 June 2020 was found from electronic databases (Web of Science, PubMed, and Scopus). The Boolean search method (including AND/OR) was used to identify the literature containing key-words and terms related to the propulsive forces in human swimming.

Eligibility criteria

Research articles were included or excluded using the criteria defined with the PICO (Methley et al., 2014) (Population, Intervention, Comparison and Outcome) strategy (Table 1). Reviews (qualitative review, systematic review, meta-analysis), overviews, conference abstracts, dissertations and thesis were excluded, as well as research articles with a sample size under eight competitive swimmers. Articles were included when published in a peer-reviewed journal. No restrictions were applied regarding language, as long as the studies included the title and abstract written in English. Titles, abstracts, and full articles were screened manually by two independent reviewers, and one single list consolidated the studies that fulfilled the eligibility criteria.

Table 1. Search strategy and inclusion/exclusion criteria based on PICO strategy.

Search terms	PICO	Inclusion criteria	Exclusion criteria
Swimming Competition	Population	Healthy competitive swimmers	Swimmers with clinical conditions Non-competitive swimmers.
Biomechanics Propulsion Forces Thrust	Intervention	Propulsive forces assessment Human participants Full or segmental swim	Resistive forces Mechanical models Specific movements (e.g., hand sculling)
Methods Assessment	Comparison	Direct methods Swimming strokes Swimmers' characteristics Training settings	Indirect methods
	Outcome	Human peak and mean propulsive force retrieved by direct methods	Non-accuracy methods with propulsive forces

Quality assessment

Two independent reviewers (CCS and MJC) performed the quality assessment of each study. Disagreements and doubts were solved by consensus, and a third reviewer (DAM) was consulted when necessary. The Downs and Black Quality Assessment Checklist (Downs & Black, 1998) was used based on the following criteria: (1) reporting; (2) external validity; (3) internal validity (bias and confounding); and (4) power. Previous systematic reviews reported the use of such tool within the sports domain (Costa et al., 2015; Hébert-Losier et al., 2013). The original version has 27 items with a maximum score of 32 points. Adaptations were made on the original version, according to the focus of included studies and the previously modified versions: (i) the term 'patient' was replaced by 'participant' and 'testing' was used instead of 'treatment' (Hébert-Losier et al., 2013); (ii) items 4, 8, 9, 14, 15, 17, 19 and 22–26 were excluded when not applicable to the study design (e.g., cross-sectional study); and (iii) the answer of item 27 was modified to 'yes' (1 point) and 'no' (0 points), rather than the five options. Methodological quality was classified as (i) low, with a score ≤50%; (ii) good, with a score between 51% and 75%, and (iii) excellent, with a score >75% (Sarmento et al., 2017). The degree of agreement between reviewers (inter-rater reliability) in the scoring procedure was obtained based on Cohen's Kappa coefficient (κ) (Cohen, 1960) and interpreted according to Landis and Koch's suggestion (Landis & Koch, 1977): (i) no agreement if $\kappa < 0$; (ii) poor agreement if $0 < \kappa < 0.19$; (iii) fair agreement if $0.20 < \kappa < 0.39$; (iv) moderate agreement if $0.40 < \kappa < 0.59$; (v) substantial agreement if $0.60 < \kappa < 0.79$; and (vi) almost perfect agreement if $0.80 < \kappa < 1.00$.

Data extraction and analysis

Articles were grouped according to the methods used to assess propulsive forces. The following data were extracted: (i) author(s) name and year of publication; (ii) study design; (iii) sample characteristics (i.e., sex, number of participants, age, competitive level); (iv) swimming stroke/condition; (v) assessment protocol (trials, time/distance, pace); and (vi) propulsive force values (peak and mean). The swimmers' chronological age was divided into four main groups: (i) <12 years-old; (ii) 12–14 years-old; (iii) 15–17 years-old; and (iv) ≥18 years-old. The Quality Index (QI) was assessed for all studies and the percentage (%) was calculated as follows: [(total points obtained)/(maximum points) x 100]. Descriptive statistics for all outcomes were expressed using mean and standard deviation (M±SD), range (minimum and maximum) and/or percentage (%). Data were analysed using Microsoft Excel 2016 spreadsheet (Microsoft Corporation Redmond, WA, USA).

Results

Search results

The initial search in Web of Science, PubMed, Scopus, and other sources yielded 2781 records. After the removal of duplicates, 2530 records were manually screened by title and abstract, which resulted in the exclusion of 2468 records. Sixty-two full-texts were assessed for eligibility and 27 of those were excluded due to the following main reasons: reduced sample size (n = 6), recreational swimmers (n = 2), not reported propulsive force values (n = 6) and indirect/non-accuracy assessment methods (n = 13). A total of 35 articles were considered for further analysis. The complete and detailed searching process is shown in Figure 1.

Quality of included studies

The reliability between both reviewers showed an almost perfect agreement ($\kappa = 0.95$) in the scoring procedure using the QI. Six studies were considered for assessment with a maximum of 32 points and 29 studies with a maximum of 17 points. A summary of the QI for each study is provided (points and %) in Tables 2 and 3. The overall QI had a mean score (± SD) of 9.3 ± 1.7 points (range: 6 to 20 points) and a percentage of 54.7 ± 9.6% (range: 35.3% to 70.6%). The mean (± SD) percentage for the studies with tethered-swimming was 54.7 ± 9.9% (range: 35.3% to 70.6%) and for studies with differential pressure sensors was 54.9 ± 8.7% (range: 47.1% to 70.6%). Higher scores in quality assessment were observed on reporting and bias subscales. The included studies scored similarly in items related to the sample characteristics description, main outcomes to be measured, estimation of random variability, statistical tests description and the main findings. Furthermore, 15 studies (out of 35) did not score in the item related to the aim of the study and hypothesis description; however, in studies with differential pressure sensors only one did not report the information of the afore- mentioned item (Pereira et al., 2015). Three studies (Amaro, Marinho et al., 2017; Dos Santos et al., 2012; Moura et al., 2014) reported the sample power (i.e., the sample size required).

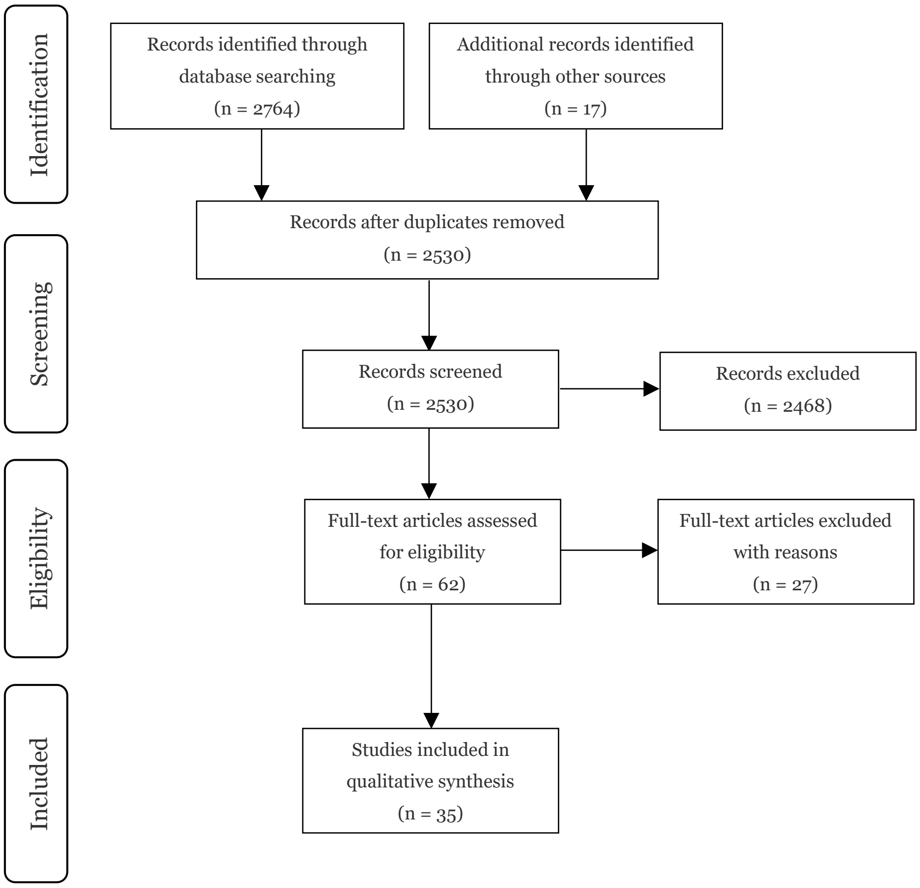

Figure 1. PRISMA (Preferred Reporting Items for Systematic reviews and Meta-analyses) flow chart.

Characteristics of included studies

The characteristics of the included studies are shown in Tables 2 and 3. The 35 included studies collected data from 1195 healthy competitive swimmers and the swimmers' mean (± SD) age was 17.4 ± 3.1 years-old. The selected sample size often ranged from 20 to 29 (20.0%), followed by 10–19 participants (17.1%), 30–39 (8.6%), >50 (8.6%), <10 (5.7%)

and 40–49 (2.9%) participants.

Table 2. Summary of the studies with tethered-swimming.

Author year	**Quality index**	**Study design**	**Sample**	**Swimming stroke/condition**	**Assessment protocol**	**Propulsive forces (N or kgf)**	
						PF_{PEAK}	PF_{MEAN}
Ruíz-Navarro et al. 2020	10 (58.8%)	Cross-sectional	♂ *n* = 16 19.6 ± 3.3 y old	Front crawl Segmental (UL)	4x30-sec 4 water flow velocities	214.58 ± 48.66 N 156.55 ± 37.00 N 125.14 ± 38.86 N 110. 11 ± 36.18 N	93.20 ± 16.92 N 60.14 ± 18.23 N 43.89 ± 15.32 N 35.49 ± 15.23 N
Oliveira et al. 2020	11 (64.7%)	Cross-sectional	♂ *n* = 53 13.6 ± 1.8 y old ♀ *n* = 75 12.5 ± 1.8 y old	Front crawl Segmental (UL)	2x30-sec Max. effort	26.0 ± 10.5 kgf (♂) 20.2 ± 6.7 kgf (♀)	-
Barbosa et al. 2020	17 (53.1%)	Longitudinal	♂ *n* = 10 ♀ *n* = 10 EG: 21.8 ± 1.9 y old CG: 22.4 ± 2.3 y old	Front crawl Full-body	2x10-sec Max. effort	-	81 ± 32 N (EG, PRE) 83 ± 33 N (EG, POS) 90 ± 31 N (CG, PRE) 92 ± 25 N (CG, PRE)
Silva et al. 2019	10 (58.8%)	Cross-sectional	♂ *n* = 23 15.7 ± 0.8 y old ♀ *n* = 26 14.5 ± 1.8 y old	Front crawl Full-body	1x30-sec N/A Experts^{1} Less Experts^{2}	186.6 ± 44.4 N (♂^{1}) 149.0 ± 56.6 N (♂^{2}) 125.8 ± 37.2 N (♀^{1}) 149.3 ± 60.6 N (♀^{2})	144.2 ± 18.9 N (♂^{1}) 126.6 ± 55.2 N (♂^{2}) 106.2 ± 18.4 N (♀^{1}) 118.9 ± 33.0 N (♀^{2})
Carvalho et al. 2019	9 (52.9%)	Cross-sectional	♂ *n* = 7 20.9 ± 3.4 y old ♀ *n* = 5 19.0 ± 2.2 y old	Front crawl Backstroke Segmental (UL)	1x30-sec N/A 10 UL^{1} 30-sec^{2}	183.20 ± 49.41 N (D ^{1}) 186.68 ± 56.17 N (ND ^{1}) 177.71 ± 49.55 N (D ^{2}) 183.44 ± 56.31 N (ND ^{2})	-
Rozi et al. 2018	10 (58.8%)	Cross-sectional	N/A; *n* = 23 15.4 ± 1.6 y old	Front crawl Full-body	1x20-sec Controlled pace (100-m time)	183.6 ± 51.5 N	72.1 ± 24.7.9 N
Andrade et al. 2018	9 (52.9%)	Cross-sectional	♂ *n* = 16 18.6 ± 1.3 y old	Front crawl Full-body	2x10-sec Max. effort	269.68 ± 17.20 N	134.86 ± 7.10 N
Strzała et al. 2019	10 (58.8%)	Cross-sectional	♂ *n* = 35 J: 17.3 ± 0.59 y old Y: 20.6 ± 1.05 y old	Front crawl Full-body	1x25-sec N/A	325.98 ± 78.14 N (J) 318.46 ± 100.53 N (Y)	116.52 ± 25.98 N (J) 123.18 ± 31.89 N (Y)
dos Santos et al. 2017	9 (52.9%)	Cross-sectional	♂ *n* = 18 21.3 ± 4.6 y old	Front crawl Full-body	1x15-sec Max. effort	130.3 ± 31.3 N (D) 116.3 ± 31.4 N (ND)	-
Amaro et al. 2017	20 (62.5%)	Longitudinal	♂ *n* = 18 G1: 12.7 ± 0.8 y old G2: 12.7 ± 0.8 y old CG: 12.6 ± 0.8 y old	Front crawl Full-body	1x40-sec Max. effort (30 sec)	-	59.86 ± 9.74 N (G1^{T1}) 58.57 ± 11.26N (G1^{T2}) 60.97 ± 9.73 N (G1^{T3}) 63.82 ± 17.20 N (G2^{T1}) 64.12 ± 17.92 N (G2^{T2}) 66.36 ± 17.32 N (G2^{T3})
Soncin et al. 2017	8 (47.1%)	Cross-sectional	♂ *n* = 12 21.8 ± 4.4 y old	Front crawl Full-body	N/A Max. effort (10 strokes)	-	117.03 ± 18.28 N
Gatta et al. 2016	9 (52.9%)	Cross-sectional	♂ *n* = 10 23.5 ± 3.4 y old	Front crawl Full-body	3x15-sec Max. effort	357 ± 77 N	181 ± 21 N
Morouço et al. 2015	7 (41.2%)	Cross-sectional	♂ *n* = 12 15.2 ± 0.9 y old ♀ *n* = 11 15.7 ± 1.4 y old	Front crawl Full-body^{1} Segmental (UL^{2} and LL^{3})	3x30-sec Max. effort	325.4 ± 27.8 N (♂^{1}) 243.7 ± 27.7 N (♂^{2}) 100.1 ± 28.2 N (♂^{3}) 222.3 ± 61.8 N (♀^{1}) 168.5 ± 36.2 N (♀^{2}) 72.0 ± 9.4 N (♀^{3})	98.8 ± 13.7 N (♂^{1}) 82.5 ± 12.0 N (♂^{2}) 35.1 ± 7.6 N (♂^{3}) 74.0 ± 12.4 N (♀^{1}) 56.9 ± 8.7 N (♀^{2}) 28.4 ± 4.6 N (♀^{3})
Morouço et al. 2015	9 (52.9%)	Cross-sectional	♂ *n* = 18 15.6 ± 2.1 y old	Front crawl Full-body	1x30-sec Max. effort	271.9 ± 28.7 N (D) 217.0 ± 29.3 N (ND)	211.2 ± 30.5 N (D) 175.7 ± 32.8 N (ND)
Loturco et al. 2015	8 (47.1%)	Cross-sectional	♂ *n* = 10 17.0 ± 0.7 y old	Front crawl Full-body	2x10-sec Max. effort	207.1 ± 27.2 N	133.2 ± 16.8 N
Amaro et al. 2014	10 (58.8%)	Cross-sectional	♂ *n* = 8 15.3 ± 1.17 y old	Front crawl Full-body	1x40-sec Max. effort (30 sec)	220.66 ± 50.94 N (^{T1}) 217.86 ± 53.07 N (^{T2})	86.10 ± 12.62 N (^{T1}) 86.92 ± 16.15N (^{T2})

Table 2. (*continued*).

Author Year	Quality index	Study design	Sample	Swimming stroke/condition	Assessment protocol	Propulsive forces (N or kgf)	
						PF_{PEAK}	PF_{MEAN}
Moura et al. 2014	11 (64.7%)	Cross-sectional	♂ n = 56 14 ± 1.8 y old	Front crawl Segmental (UL)	2x30-sec Max. effort	17.5 ± 8.5 kgf	-
Morouço et al. 2014	10 (58.8%)	Cross-sectional	♂ n = 34 17.2 ± 2.72 y old	Front crawl Full-body	1x30-sec Max. effort	331.8 ± 40.6 N	112.7 ± 15.6 N
Barbosa et al. 2013	10 (58.8 %)	Cross-sectional	♂ n = 14 20.0 ± 3.7 y old	Front crawl Full-body	2x10-sec Max. effort 4 sizes of hand paddles (HP)	278 ± 29 N (without HP) 293 ± 39 N (small) 310 ± 36 N (medium) 324 ± 39 N (large) 338 ± 40 N (extra-large)	148 ± 10 N (without HP) 151 ± 14 N (small) 156 ± 14 N (medium) 159 ± 17 N (large) 156 ± 19 N (extra-large)
Morouço et al. 2012	10 (58.8%)	Cross-sectional	♂ n = 7 16.6 ± 1.0 y old ♀ n = 6 15.8 ± 0.8 y old	Front crawl Full-body	1x30-sec Max. effort	243.6 ± 60.15 N	89.8 ± 22.13 N
dos Santos et al. 2012	12 (70.6%)	Cross-sectional	♂ n = 28 14.0 ± 1.8 y old	Front crawl Segmental (UL)	2x30-sec Max. effort	22.6 ± 8.1 kgf	-
Neiva et al. 2011	9 (52.9%)	Cross-sectional	♂ n = 10 15.3 ± 0.95 y old	Front crawl Full-body	2x30-sec Max. effort	299.62 ± 77.56 N 351.33 ± 81.85 N (WU)	91.65 ± 14.70 N 103.97 ± 19.11 N (WU)
Morouço et al. 2011	8 (47.1%)	Cross-sectional	♂ n = 20 19.0 ± 2.88 y old ♀ n = 12 15.3 ± 1.68 y old	Front crawl (Fr) Backstroke (Bck) Breaststroke (Brs) Butterfly (Fly) Full-body	2x30-sec Max. effort	232.6 ± 63.2 N (Fr) 211.6 ± 47.5 N (Bck) 513.0 ± 153.9 N (Brs) 394.4 ± 134.4 N (Fly)	92.8 ± 33.7 N (Fr) 99.9 ± 29.1 N (Bck) 115.6 ± 30.5 N (Brs) 88.9 ± 34.9 N (Fly)
Morouço et al. 2011	10 (58.8%)	Cross-sectional	♂ n = 10 14.9 ± 0.74 y old	Front crawl Full-body1 Segmental (UL[2] and LL[3])	3x30-sec Max. effort	-	95.16 ± 11.66 N[1] 80.33 ± 11.58 N[2] 33.63 ± 7.53 N[3]
Morouço et al. 2010	6 (35.3%)	Cross-sectional	♂♀ n = 419 N/A	Front crawl Full-body	1x30-sec Max. effort	283.6 ± 45.02 N (♂) 196.8 ± 29.38 N (♀) 248.9 ± 58.33 N (♂♀)	101.9 ± 18.01 N (♂) 71.3 ± 2.98 N (♀) 89.7 ± 20.71 N (♂♀)
Papoti et al. 2007	14 (43.8%)	Longitudinal	♂ n = 11; ♀ n = 3 16.0 ± 1.3 y old	Front crawl Full-body	1x30-sec Max. effort	-	86.56 ± 13.05 N (PRE) 89.88 ± 16.05 N (POS)
Papoti et al. 2003	7 (41.2%)	Cross-sectional	N/A; n = 13 N/A	Front crawl Full-body	2x30-sec Max. effort	-	86.6 ± 3.6 N ([T1]) 87.6 ± 4.0 N ([T2])
Hooper et al. 1998	12 (37.5%)	Longitudinal	♂ n = 12; ♀ n = 15 15.0 ± 1.6 y old	Front crawl Full-body	N/A Max. effort (20 strokes)	167.2 ± 58.8 N ([T1]) a 157.7 ± 51.9 N ([T2]) a 165.5 ± 47.0 N ([T3]) a 177.3 ± 49.0 N ([T4]) a	-
Yeater et al. 1981	7 (41.2%)	Cross-sectional	N/A; n = 18 N/A	Front crawl (Fr) Backstroke (Bck) Breaststroke (Brs) Full-body[1] Segmental (UL[2] and LL[3])	1xN/A Max. effort	384 ± 77 N (Fr[1]) 693 ± 231 N (Brs[1])	191 ± 41 N (Fr[1]) 97 ± 23 N (Fr[2]) 119 ± 35 N (Fr[3]) 156 ± 43 N (Bck[1]) 188 ± 51 N (Brs[1]) 126 ± 38 N (Brs[2]) 138 ± 47 N (Brs[3])

Data are reported as mean ± standard deviation unless specified otherwise. ♂, men/boy; ♀, women/girl; %, percentage; [a], mean ± standard error of the mean; [T1,T2,T3,T4], different periods or trials; CG, control group; D, dominant limb; EG, experimental group; J, junior group; kgf, kilogram-force; LL, lower-limbs; N, Newton; *n*, number of participants; ND, non-dominant limb; N/A, not available; PF, propulsive force; PF_{MEAN}, mean propulsive force; PF_{PEAK}, peak propulsive force; PRE, pre-test; POS, post-test; UL, upper-limbs; WU, warm-up; Y, youth group; y old, years-old.

Twenty-nine studies (82.9%) measured propulsive forces with tethered-swimming (Amaro et al., 2014; Amaro, Marinho et al., 2017; Andrade et al., 2018; A. C. Barbosa et al., 2013, 2020; Carvalho et al., 2019; K. B. Dos Santos et al., 2017; M. A. Dos Santos et al., 2012; Gatta et al., 2016; Hooper et al., 1998; Loturco et al., 2015; Morouço, Keskinen et al., 2011; Morouço, Marinho, Fernandes et al., 2015; Morouço, Marinho, Izquierdo et al., 2015; Morouço et al., 2014; Morouço, Neiva et al., 2011; Morouco et al., 2010; Morouço et al., 2012; Moura et al., 2014; Neiva et al., 2011; Oliveira et al., 2021; Papoti et al., 2007, 2003; Rozi et al., 2018; Ruiz-Navarro et al., 2020; Silva et al., 2019; Soncin et al., 2017; Strzała et al., 2019; Yeater et al., 1981) and six studies (17.1%) with differential pressure sensors (T. M. Barbosa et al., 2020; Bottoni et al., 2011; Morais et al., 2019; Ng et al., 2020; Pereira et al., 2015; Tsunokawa et al., 2018). The studies using the tethered-swimming found values ranging between ≈100–693 N for PF_{PEAK} and ≈35–211 N for PF_{MEAN}. Meanwhile, the studies using pressure sensors showed values of PF_{PEAK} and PF_{MEAN} ranging between ≈64–124 N and ≈27–55 N, respectively. Furthermore, 62.9% of the included studies reported the peak and mean propulsive force values while 17.1% and 20.0% showed only the peak or mean propulsive force values (respectively).

Table 3. Summary of the studies with differential pressure sensors.

Author Year	Quality index	Study design	Sample	Swimming stroke/condition	Assessment protocol	Propulsive forces/pressures (N or hPa)	
						PF_{PEAK}	PF_{MEAN}
Barbosa et al. 2020	10 (58.8%)	Longitudinal	♂ n = 12 23.50 ± 3.35 y old	Front crawl Segmental (UL)	1x25-m Max. effort	72.3 ± 11.6 N (Non-PAP) 80.9 ± 11.9 N (PAP)	27.9 ± 7.7 N (Non-PAP) 31.9 ± 8.1 N (PAP)
Ng et al. 2019	9 (52.9%)	Longitudinal	♂ n = 16 22.13 ± 3.84 y old	Front crawl Segmental (LL)	1x25-m Max. effort	92.7 ± 15.8 N (Non-PAP) 105.2± 21.1 N (PAP)	35.2 ± 7 N (Non-PAP) 39.6 ± 12.4 N (PAP)
Morais et al. 2019	12 (70.6%)	Cross-sectional	♂ n = 12; ♀n = 6 15.81 ± 1.62 y old	Front crawl Full-body	3x25-m Max. effort	64.63 ± 8.19 N (D) 64.49 ± 10.69 N (ND)	37.88 ± 6.61 N (D) 36.18 ± 6.42 N (ND)
Tsunokawa et al. 2018	9 (52.9%)	Cross-sectional	♂ n = 8 20.4 ± 1.3 y old	Front crawl Segmental (UL)	2x16-m Max. effort	-	44.86 ± 9.06 N (Hand) 51.07 ± 9.36 N (HP)
Pereira et al. 2015	8 (47.1%)	Cross-sectional	♂ n = 9; ♀n = 5 18.4 ± 4.9 y old	Butterfly Full-body	3x25-m Max. effort	124.8 ± 39.6 N (D) 110.7± 36.7 N (ND)	55.7 ± 14.7 N (D) 51.2 ± 14.7 N (ND)
Bottoni et al. 2011	8 (47.1%)	Cross-sectional	♂ n = 20 N/A	Front crawl Full-body	1x25-m Controlled pace (1500-m time)	55.6 ± 12.1 hPa	28.7 ± 4.5 hPa

Data are reported as mean ± standard deviation. ♂, men/boy; ♀, women/girl; %, percentage; D, dominant limb; hPa, hectopascal; HP, hand paddles; LL, lower-limbs; N, Newton; n, number of participants; N/A, not available; ND, non-dominant limb; PAP, post-activation potentiation; PF, propulsive force; PF_{MEAN}, mean propulsive force; PF_{PEAK}, peak propulsive force; UL, upper-limbs; y old, years-old.

The propulsive force was mainly assessed during the front crawl depicting 88.6% of the total included studies (Amaro et al., 2014; Amaro, Marinho et al., 2017; Andrade et al., 2018; A. C. Barbosa et al., 2020; K. B. Dos Santos et al., 2017; M. A. Dos Santos et al., 2012; Gatta et al., 2016; Hooper et al., 1998; Loturco et al., 2015; Morouço, Marinho, Fernandes et al., 2015; Morouço, Marinho, Izquierdo et al., 2015; Morouço et al., 2014; Morouço, Neiva et al., 2011; Morouco et al., 2010; Morouço et al., 2012; Moura et al., 2014; Neiva et al., 2011; Ng et al., 2020; Oliveira et al., 2021; Papoti et al., 2007, 2003; Rozi et al., 2018; Ruiz-Navarro et al., 2020; Silva et al., 2019; Soncin et al., 2017; Strzała et al., 2019; Tsunokawa et al., 2018; Yeater et al., 1981). One study analysed the butterfly stroke (Pereira et al., 2015) and three were conducted with multiple swimming strokes (Carvalho et al., 2019; Morouço, Keskinen et al., 2011; Yeater et al., 1981). As for the front crawl the values of propulsive force were around 65–384 N for PF_{PEAK} and 28–211 N for PF_{MEAN}. For backstroke, there was a PF_{PEAK} of ≈211 N and a PF_{MEAN} ranging between ≈99–156 N. For the butterfly stroke, the values were between ≈110–124 N in PF_{PEAK} and ≈51–55 N in PF_{MEAN}. The higher values were shown for breaststroke in PF_{PEAK} (range: ≈513–693 N), and PF_{MEAN} ranging between ≈115–188 N.

According to the segmental actions, nine studies (T. M. Barbosa et al., 2020; M. A. Dos Santos et al., 2012; Morouço, Marinho, Izquierdo et al., 2015; Morouço, Neiva et al., 2011; Moura et al., 2014; Oliveira et al., 2021; Ruiz-Navarro et al., 2020; Tsunokawa et al., 2018; Yeater et al., 1981) were conducted in front crawl with upper-limbs showing propulsive forces between ≈72–255 N and ≈27–97 N for PF_{PEAK} and PF_{MEAN}, respectively. Four front crawl studies (Morouço, Marinho, Izquierdo et al., 2015; Morouço, Neiva et al., 2011; Ng et al., 2020; Yeater et al., 1981) reported lower-limbs data ranging between ≈72–105 N in PF_{PEAK} and ≈28–119 N in PF_{MEAN}. A single study (Yeater et al., 1981) separated propulsive forces by upper- and lower-limbs in breaststroke with a PF_{MEAN} of ≈126 N and ≈138 N, respectively.

Most studies analysed only men/boys (60.0%) or a mixed-sex group (i.e., men/boys and women/girls; 31.4%). None of the studies was performed with only women/girls and three studies (8.6%) (Papoti et al., 2007; Rozi et al., 2018; Yeater et al., 1981) did not specify the participants' gender. However, men were able to show a higher range of PF_{PEAK} (≈64–357 N vs. ≈72–222 N) and PF_{MEAN} (≈27–211 N vs. ≈28–119 N) than their women counterparts (Morouço, Marinho, Izquierdo et al., 2015; Morouco et al., 2010; Oliveira et al., 2021; Silva et al., 2019). The chronological age most often recruited ranged between 15 and 17 years-old (n = 14), as well as the age-group equal or above 18 years-old (n = 14). Two studies (Morouço, Keskinen et al., 2011; Strzała et al., 2019) were considered in both age-groups as they analysed competitive swimmers with a chronological age ranging from 15 to 20 years-old. Moreover, five studies (Amaro, Marinho et al., 2017; M. A. Dos Santos et al., 2012; Morouço, Neiva et al., 2011; Moura et al., 2014; Oliveira et al., 2021) reported the age-group of 12 to 14 years-old and four studies (Bottoni et al., 2011; Morouco et al., 2010; Papoti et al., 2003; Yeater et al., 1981) did not reveal the age. The age-group below 12 years-old was not considered in the included studies. Seventeen studies (48.6%) reported the competitive level of swimmers as international/high (Carvalho et al., 2019; Gatta et al., 2016; Loturco et al., 2015; Morouço, Keskinen et al., 2011), national (Amaro et al., 2014; Amaro, Marinho et al., 2017; Morouço, Marinho, Izquierdo et al., 2015; Morouço et al., 2012; Rozi et al., 2018) or regional/local (T. M. Barbosa et al., 2020; K. B. Dos Santos et al., 2017; Ng et al., 2020; Ruiz-Navarro et al., 2020). Such studies showed values of P_{FPEAK} between ≈186–513 N,

≈183–351 N and ≈80–215 N, whereas PF_{MEAN} ranged between ≈115–181 N, ≈66–104 N and ≈31–93 N, in swimmers classified as international, national, and regional, respectively.

A large number of studies reported a cross-sectional design (82.6%), whilst longitudinal design was used in six studies (17.1%). Furthermore, few studies analysed propulsive forces according to dry-land and in-water programmes (Amaro, Marinho et al., 2017; Hooper et al., 1998; Papoti et al., 2007), warm-up (T. M. Barbosa et al., 2020; Neiva et al., 2011; Ng et al., 2020), and propulsion devices (A. C. Barbosa et al., 2013, 2020).

Discussion and implications

This review aimed to summarise the available data about human propulsive forces in competitive swimming measured by direct assessment methods. A good methodological quality was found for the included studies. Meanwhile, eight studies showed a low methodological quality with a score below 50%. Tethered-swimming and differential pressure sensors enable to assess propulsive forces directly but showing different range values. Large evidence was found in tethered-swimming, whereas differential pressures demonstrated a recently boost. Different propulsive forces values arise from different methods and competitive swimming strokes or segmental actions, swimmers' characteristics, and training settings.

Propulsive forces and direct methods

Propulsion in human swimming is one of the most challenging areas of research. Our results demonstrated that 82.5% of the included studies were published in the last decade (2010–2020), which reveals a boosted interest in this topic. Through this period, large efforts were made to provide new and more accurate tools (Sacilotto et al., 2014). The tethered swimming and pressure sensors became the easiest and most popular apparatus to be used. As such, in this review, the studies were gathered accordingly. Twenty-nine studies (82.9%) measured propulsive forces using tethered-swimming. Only six studies (17.1%) reported propulsive forces values acquired through differential pressures sensors. It is worth noting that most of the included studies with differential pressure sensors (83.3%) were published between 2015 and 2020. The higher number of studies shown for the tethered method can be explained by the common use in competitive squads (Andrade et al., 2018).

The values obtained by both methods show mixed-findings. Those differences may rely on the 'nature' of the assessment. For instance, tethered-swimming measures the sum of all forces acting on the body during a segmental (i.e., only upper- or lower-limbs) or full-body condition (Morouco et al., 2010), whereas the differential pressure sensors measure the propulsive force by each body limb (i.e., hand or foot) (T. M. Barbosa et al., 2020). Tethered-swimming consists of remaining connected to a load cell/strain gauge by a steel cable attached to a rigid surface (e.g., the edge of the pool or the starting block) and to a belt tied to the swimmer's waist (Yeater et al., 1981). This method allows assessing individual force–time curves with a 'free motion' for the limbs although the swimmer remains tethered without forward displacement (i.e., stationary swimming) (Morouço, Keskinen et al., 2011). Here, some concerns have been raised on the water flow surrounding the swimmer (T. M. Barbosa et al., 2020; Soncin et al., 2017) such as the absence of the drag forces (Amaro, Morouço et al., 2017) or slight changes in stroke pattern (Psycharakis et al., 2011; Yeater et al., 1981), though Morouço et al. (2014) reported non-significant changes in the stroke pattern. The assessment of propulsive forces at a water flow velocity of zero seems to underpin the swimmers' strength potential rather than the ability to apply force on the water (Amaro et al., 2014; Ruiz-Navarro et al., 2020). Moreover, Samson et al. (2018) found that such method tends to overestimate the propulsive force when compared to the 'free-swimming' condition at a sprinting pace. On the other hand, the differential pressure sensors allow a displacement throughout the water without any constraints on the body or limbs and are very similar to 'free-swimming' (Bottoni et al., 2011; Morais et al., 2020). Those sensors measure the water pressure differences between the palmar/plantar surface (low-pressure field) and dorsal surface (high-pressure field) during an unsteady motion (Morais et al., 2019; Ng et al., 2020; Pereira et al., 2015). The force output (N) is derived by multiplying the pressure by the area (Tsunokawa et al., 2018). Carrying several pressure sensors might lead to some technical constraints (T. M. Barbosa et al., 2020) and this matter could increase the resistive forces due to the change of hand/foot area surface.

Although tethered-swimming has been suggested as a valid/reliable method (Amaro et al., 2014; Nagle Zera et al., 2021), and differential pressure sensors as a method with accuracy (Havriluk, 1988; Tsunokawa et al., 2018), future research should try to understand if both methods are effective, valid and reliable to assess propulsive forces (i.e., a better external/internal validity). It remains unanswered whether the results from a stationary effort are more representative than those conducted in a more ecological validity environment (i.e., swimming with displacement). Likewise, an agreement between the tethered-swimming and differential pressure sensors is needed. Although the literature is scarce, we may speculate that using differential pressure sensors would be preferable since there are drag forces acting on the swimmer´s body in an opposite direction to the movement. This may provide a condition closer to the 'free-swimming' and more user-friendly in the training field.

Propulsive forces and swimming stroke or segmental action

Swimming strokes can be categorised as having alternated (front crawl and backstroke) or simultaneous (breaststroke and butterfly) actions. The higher values were shown for breaststroke in PF_{PEAK}, whereas PF_{MEAN} tended to be more closely to the remaining strokes. Those interval differences may depend on the underwater trajectories and actions that are distinct between strokes. Body limbs feature unique anteroposterior and mediolateral underwater paths (T. M. Barbosa, Bragada et al., 2010). Through this, different stroke profiles in individual force–time curves are obtained according to each swimming stroke (Morouço, Keskinen et al., 2011). It is well-established that front crawl is the fastest and most economical stroke covering a wide range of distances in official events (T. M. Barbosa, Bragada et al., 2010; Deschodt et al., 1999). Breaststroke is the slowest one but showing a higher PF_{PEAK}. Indeed, the propulsion generated by lower-limbs in breaststroke presents a horizontal orientation leading to higher propulsive forces (Vorontsov, 2000). As propulsion phases may generate higher peak forces in breaststroke and butterfly stroke (Magel, 1970; Morouço, Keskinen et al., 2011), the recoveries may slow down due to an increased drag. This promotes a higher intracycle velocity variation increasing energy cost (T. M. Barbosa et al., 2006). Such variations are greater at breaststroke due to the underwater limbs recovery and the gliding phases (Seifert et al., 2011). Thus, this may explain why breaststroke shows a higher PF_{PEAK} comparing to the front crawl and backstroke (Morouço, Keskinen et al., 2011; Yeater et al., 1981), but not a greater PF_{MEAN}. Research in this topic is scarce and limited to one single stroke. Further attempts should try to analyse more than one stroke style and better characterise the swimming action.

A few of the articles admitted in this review also attempted to understand the propulsive forces dissecting it by body segmental actions. Here there is some coherence that upper-limbs are responsible for the major contribution for front crawl propulsion (Bartolomeu et al., 2018), mainly due to the trajectory and orientation of swimmers' hand during the displacement on the water (Morais et al., 2019). Despite counting only 10–15% of the overall swim speed (Bartolomeu et al., 2018; Deschodt et al., 1999), human kicking should not be overlooked (Ng et al., 2020). Morouço, Marinho, Izquierdo et al. (2015) found that kicking contributes ≈31% to the force production in front crawl. The values found in breaststroke for kicking are higher than those retrieved by arms pulling (Yeater et al., 1981). So, we might suspect that the real contribution of lower-limbs for the sum of propulsion is not as reduced and can be distinct depending on the stroke. In fact, there is evidence that the sum of propulsive forces of each segmental action alone is greater than the one shown in a full-body swim (Morouço, Marinho, Izquierdo et al., 2015; Yeater et al., 1981). The full-body swim might not reach such higher propulsive forces due to the turbulence surrounding the body which affects the kicking (Yeater et al., 1981). Moreover, the upper- and lower-limbs coordination adopted at full-body swim is a challenging task constraint for humans that may lead to loss of efficiency and reduced propulsion (Deschodt et al., 1999). Concerning this topic, the swimmer needs to concentrate on the various limbs, which does not happen while pulling or kicking alone. Although there is some understanding in this field, deeper research is needed. There is the possibility to clarify the real contribution for the propulsion by each segmental action within each competitive stroke. The propulsive force profile according to the different pathways of upper- and lower-limbs in all four competitive swimming strokes is also an important issue since no evidence was found.

Propulsive forces and swimmers' characteristics

Whilst much debate surrounds the performance key-factors according to the biophysical approach, mixed-findings likely underlie the gender effect. At least four studies analysed propulsive forces between genders. Men were able to show a higher range of PF_{PEAK} and PF_{MEAN} than their women counterparts (Morouço, Marinho, Izquierdo et al., 2015; Morouco et al., 2010; Oliveira et al., 2021; Silva et al., 2019). These studies contribute to solid evidence that men are able to produce a greater amount of strength than women in both land and water environments (Hunter & Enoka, 2001; Stoll et al., 2000). Within the water background, this can be explained by the interactions between motor control, anthropometric and kinematic features (T. M. Barbosa, Bragada et al., 2010). Men are faster mostly due to the higher generated propulsion (Morouço, Marinho, Izquierdo et al., 2015). When properly oriented, they are able to increase propulsive forces in larger surface areas (Morais et al., 2013). They are also taller and display a higher arm span which benefits stroke length (Silva et al., 2019). Fundamentally, the swimming velocities in men/boys seem more related to the PF_{PEAK} of upper-limbs whereas women/girls seem more dependent on PF_{MEAN} (Morouço, Marinho, Izquierdo et al., 2015). Despite that, one single study was conducted to assess the estimated relative contribution (in %), according to the PF_{PEAK}. The results showed a similar contribution of propulsive force for upper-limbs (♂: 70.3%; ♀: 66.6%) and lower-limbs (♂:29.7%; ♀:33.4%) by men and women (Morouço, Marinho, Izquierdo et al., 2015). This may indicate that a deeper interpretation of propulsive forces should consider secondary characteristics, such as chronological/biological age and competitive level.

Solely one study attempted to show propulsive data according to different age cohorts. Surprisingly, no differences in PF_{PEAK} and PF_{MEAN} were found between junior (17.3 ± 0.59 years-old) and senior (20.6 ± 1.05 years-old) swimmers (Strzała et al., 2019). There is a gap in the state of the art since most of the studies to date included participants above 15 years-old. The absence of research at younger ages (i.e., from 10 to 14 years-old) is probably due to ethical issues (T. M. Barbosa, Costa et al., 2010) or because deterministic models highlight other factors deemed important for performance beyond the propulsive force (T. M. Barbosa et al., 2013). In this way, there is a good chance in the future to link the growth/maturation process to adaptations in propulsive forces. For instance, Oliveira et al. (2021) found that all anthropometric and body composition variables were positively associated with the PF_{PEAK}, this being mediated by biological maturation. In addition, Moura et al. (2014) reported the percentage of body fat and height as predictors of the upper-limbs propulsive force after controlling the maturational stage.

Regarding the swimmers' expertise, there is also a few information pointing us in the right direction. At least one study noted no differences between expert and non-expert in PF_{PEAK} and PF_{MEAN} (Silva et al., 2019). So, further attempts should try to clarify how propulsive forces change according to expertise in a broad range of velocities.

Propulsive forces and training effects

Different study designs have been employed to assess biomechanical parameters and to link them with swimming performance (Costa et al., 2015). Cross-sectional designs are widely undertaken in swimming research (Costa et al., 2010), which is in line with our results (29 out of 35 studies). Monitoring the changes over time provides fundamental insights into the performance improvements and the long- or short-term training effects (Costa et al., 2010), but parallel changes cannot be provided by cross-sectional designs (Zacca et al., 2019). This type of study is limited to one single assessment point in time (Costa et al., 2015) and does not provide cues about the cause-effect relationship through time (Ferreira et al., 2016). Longitudinal data allows to track the swimmers' characteristics and understand variations in distinct phases of the season and off-season training (Zacca et al., 2019), to predict their performance throughout a given time of period (Costa et al., 2010), and to help coaches to achieve realistic training goals (Pyne et al., 2001). In this review, no more than six studies were classified as having a longitudinal research type. Those presented interventions ranging between 1 and 10 weeks and concerned the implementation of specific training.

Specific training is considered a key-factor to boost performance (Muniz-Pardos et al., 2019). Here, the use of various training regimes and/or tools is welcome to increase propulsive forces. Studies focused on the effect of dry-land training, tapering, warm-up, or propulsion devices were included. Dry-land strength gains 10 weeks later in prepubescent swimmers (2.1 ± 0.4 Tanner stages by self-evaluation) showed a null transfer to in- water force production (Amaro, Marinho et al., 2017). On the other hand, reducing around 2 weeks was enough to get improvements in PF_{PEAK} (Hooper et al., 1998) and PF_{MEAN} (Papoti et al., 2007). The competitive level and the age may have influenced in the transferability of the strength, which lead to a mixed-findings. Standard warm-up protocols (Neiva et al., 2011) or warm-up with post-activation potentiation (T. M. Barbosa et al., 2020; Ng et al., 2020) also showed to be effective in increasing propulsive forces from 12% to 19%. Compensatory-mechanism induced by training with devices has also been a topic of interest. Hand-paddles are regularly used in an attempt to enlarge the hand surface area. Although the use of hand paddles imposes a significant increase in PF_{PEAK} (A. C., Barbosa et al., 2013), their long-term effect (e.g., 4 weeks) is questionable (A. C. Barbosa et al., 2020).

The little research on this topic is restricted to short-term effects not allowing to go further on this discussion. Probably, monitoring changes over longer periods would provide new insights about the real effects of several specific training regimes (e.g., dry-land training with free-weights, elastics and in-water training with propulsion and add-resistance materials). Moreover, to date, no study was able to provide deeper insights into how propulsive forces change within or between competitive seasons in response to a traditional training periodisation (two or three peak form).

Conclusions

Based on the overall findings of this systematic review, the values of the propulsive force rely on different direct assessment methods, swimming strokes and segmental actions, swimmers' characteristics, and training settings. Thus, the competitive swimming stroke, the number of body limbs and gender are factors determining the propulsive force. Tethered-swimming and differential pressure sensors allow directly measuring propulsive forces, wherein higher range values were observed for tethered-swimming. Although both have been suggested as accurate methods to measured propulsive forces, an agreement between the two was not reported which leads to mixed-findings. The breaststroke showed higher values of PF_{PEAK}, whereas PF_{MEAN} tended to be closer to the remaining strokes and the upper-limbs seem to be responsible for the major contribution in front crawl propulsion. Mixed-findings were found due to the swimmer's characteristics. Men are more able to show higher propulsive forces than women counterparts. Meanwhile, there is a gap in the state of the art on propulsive forces in competitive swimmers below 15 years-old and it appears that junior and senior competitive swimmers promote similar exertion. The competitive level does not seem to influence the propulsion, but higher expertise leads to a greater amount of applied force. Moreover, warm-up seems effective in increasing propulsion, but short-term effects regarding training programmes do not promote adaptations in propulsive force.

Chapter 3. Experimental studies: assessment tools

Study 2. A comparison of tethered swimming and pressure sensors to measure in-water force in young competitive swimmers

Abstract

The purpose of this study was to compare the in-water force of young competitive swimmers using tethered swimming and differential pressure sensors. Thirty-one swimmers (16 girls and 15 boys) were randomly assigned to perform two in-water tests. Swimmers completed two maximum bouts of 25m front crawl with a differential pressure system and a 30s maximum bout with an attached load cell (tethered-swimming). The peak force (F_{PEAK}, in N) of dominant and non-dominant upper limbs was retrieved for further analysis. Comparison between methods revealed significant differences in all force variables ($p \leq 0.05$) and the biases (mean differences) were large in girls (F_{PEAK} dominant, 45.89 N; F_{PEAK} non-dominant, 43.79 N) and boys (F_{PEAK} dominant, 67.26 N; F_{PEAK} non-dominant, 61.78 N). Despite that, simple linear regression models between the two methods showed significant relationships with a moderate effect in all variables for girls, whereas in boys a high and moderate effect was verified for F_{PEAK} of dominant and non-dominant limbs (respectively). It seems that using pressure sensors and tethered swimming leads to different F_{PEAK} values in young competitive, where correction factors are needed to compare data between both methods.

Key words: hand force; load cell; sensors; correction factor; swimming

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Introduction

In competitive swimming the ability to effectively apply force in the water plays a crucial role in the swimmers' forward displacement. The generated force defines the coordination between the limbs and characterizes how the swimmer behaves in each stroke cycle. As it is a topic of great importance for the training process, there is a regular and systematic innovation of different methods to measure and control these forces as a key factor (Santos et al., 2021). From these cutting-edge set-ups, experimental methods allow researchers to directly obtain individual force-time curves and consequently link them to performance (i.e., swimming velocity).

The use of tethered-swimming and differential pressure sensors has become the easiest available methods to measure in-water force as both are less time-consuming compared to other methods. However, some mixed-findings have been documented when using these methods, which may be due to the nature of the assessments (Santos et al., 2021). In tethered-swimming, the swimmer remains connected to a load cell/strain gauge by a non-elastic cable with no forward displacement (Yeater et al., 1981). This method appears to sustain the swimmer's strength potential rather than the ability to apply force effectively (Ruiz-Navarro et al., 2020), leading to overestimation (Samson et al., 2018). The use of tethered-swimming in a flume can help to overcome this aspect (i.e., absence of drag) due to the existence of a water flow that will influence the swimmer's speed (Ruiz-Navarro et al., 2022). However, advanced technology (e.g., swim flume, sensors) may not be available in all competitive squads due to cost/accessibility (Mooney et al., 2015). In contrast, with differential pressure sensors, the swimmer can move through the water and the forces of each limb (i.e., hand or foot) are estimated (Santos et al., 2021). This method allows for a more "free swimming" condition, but the two sensors only measure the resultant force of the hand rather than the effective propulsive force. Nevertheless, the two-hand sensors set-up (Aquanex System) has been increasingly used (e.g., Bartolomeu et al., 2022; Barbosa et al. 2020), as it allows an assessment in a more ecologically valid environment without constraints on stroke mechanics and efficiency (Santos et al., 2022a).

Although there is still no consensus on a gold standard method for measuring propulsive force, tethered-swimming (Amaro et al., 2014) and pressure sensors have been found to be reliable (Santos et al., 2022b). Most studies were performed using one of these methods individually (e.g., Morouço et al., 2014). To date, no research has been carried out to verify agreement or compare these two methods. However, comparisons between other methods/procedures have already been made in swimming (Barbosa et al., 2015;

Barbosa et al., 2018), canoe polo (Löppönen et al., 2022), and cycling (Forte et al., 2020). In the specific case of swimming, Barbosa et al. (2015) found that using different procedures to measure passive drag can lead to data bias. The same authors suggested the application of a correction factor to adjust the estimates. Various swimming squads and laboratories still differ in the type of set-up they have at their disposal for their daily assessments. Thus, it becomes extremely useful to provide comparable data between tethered swimming and pressure sensors. Researchers and practitioners are also interested in gaining deeper insight into data in ecological settings (Barbosa et al., 2021), such as “free-swimming”. Thus, ensuring that the availability or costs of different tools (e.g., sensors) do not impair training monitoring can help coaches to use only the resources available in the squads (e.g., tethered-swimming). Therefore, the aim of this study was to compare the in-water force of young swimmers using tethered swimming and differential pressure sensors. It was hypothesized that, as argued by Santos et al. (2021), there would be no agreement between the methods and a correction factor should be used for accurate estimates between the methods.

Materials and Methods

Participants

Thirty-one highly trained (Mckay et al., 2022) swimmers (16 girls and 15 boys) volunteered to participate in this study (Table 1). Swimmers were recruited from local swimming squads and assessed at the end of the third macrocycle (competitive peak form). The inclusion criteria for the participants were: (i) being previously familiar with the hand differential pressure system and tethered swimming; (ii) having a minimum of two years in competitive swimming in regional or national events; (iii) practicing more than four swim training sessions per week; and (iv) not having suffered any injuries in the past six months. Swimmers who did not meet these criteria from the beginning of the season until the data collection were not considered. The swimmers’ parents or guardians were informed about the benefits and experimental risks before signing a written informed consent form. All procedures were in accordance with the Declaration of Helsinki and approved by the Institutional Ethics Committee of the University of Beira Interior (code: CE-UBI-Pj-2020-058).

Table 1. Characteristics of the swimmers.

Variables	Girls (n = 16)	Boys (n = 15)
Age (yo)	12.00±0.50	12.87±0.62
Body mass (kg)	47.46±9.71	49.94±8.11
Body height (cm)	154.84±6.73	157.81±7.64
HSA dominant (cm^2)	99.95±8.87	107.13±12.07
HSA non-dominant (cm^2)	100.71±7.95	108.85±13.34
FINA points (50-m freestyle)	226.88±43.90	221.17±37.32

yo, years-old; kg, kilogram; cm^2, square centimetre.

Data collection

A cross-sectional research design was conducted to measure in-water forces using a differential pressure system (Figure 1, Panel A) and tethered-swimming (Figure 1, Panel B). Participants attended two test sessions on different days with a maximum interval of 48h. At the beginning of the first session, the swimmers underwent anthropometric and body composition tests wearing only a textile swimsuit and a cap. Height (in cm) and body mass were measured with a digital stadiometer (SECA, 242, Hamburg, Germany) and a scale (TANITA, BC-730, Amsterdam, Netherlands), respectively. The hand surface area (HSA, in cm^2) for the dominant and non-dominant sides was measured by digital photogrammetry (Moreira et al., 2014). Swimmers placed each hand on a flat surface with a 2D calibration frame (3x3 cm) and from there all images were exported to an on-screen digitizer that allows accurate measurement of areas (Universal Desktop Ruler, v3.8, AVPSoft, USA). The swimmers' hand dominance was assessed by self-report.

The in-water experimental testing was carried out in a 25m indoor swimming pool (water temperature: 27.5°C; relative humidity: 60%) and force measurements were performed separately during the two test sessions. A standardized warm-up (400m swim, 100m pull, 100 kick, 4x50 at increasing speed, 200m easy swim) was performed individually by each swimmer before the two data collection (Morouço et al., 2018). Although all swimmers were familiar with the two force methods prior to testing, they underwent a familiarisation protocol with each procedure. In addition, all participants were asked to abstain from intense exercise the day before the tests to avoid data bias due to fatigue.

Pressure sensors test

Swimmers completed two maximum bouts of 25m front crawl (full-body) with their normal breathing pattern for sprint events. The test began with an in-water push-off without gliding controlled by an auditory signal. A 30min active rest was applied between each bout. Swimmers were randomly assigned for the first bout and followed the same order in the second. A differential pressure system composed of two hand sensors (Type A, Swimming Technology Research, Richmond, VA, USA) positioned between the third and fourth proximal phalanges and metacarpals was used to measure the pressure differences between the palmar and dorsal surfaces of both hands. The resultant force of the hand (in N) was obtained by the system from the product of differential pressure of the hand surface area of each swimmer.

A two-channel A/D converter connected to a laptop with the Aquanex software (v.4.1, Model DU2, Swimming Technology Research, Richmond, VA, USA) was used to acquire data in real-time. Swimmers carried the system with elastic straps on their shoulders and arms (Figure 1, Panel A). At the beginning of each bout, swimmers were reminded to keep their hands immersed for 10s at the waistline level to calibrate the system. Data was acquired with a sampling frequency of 100 Hz for each maximum bout.

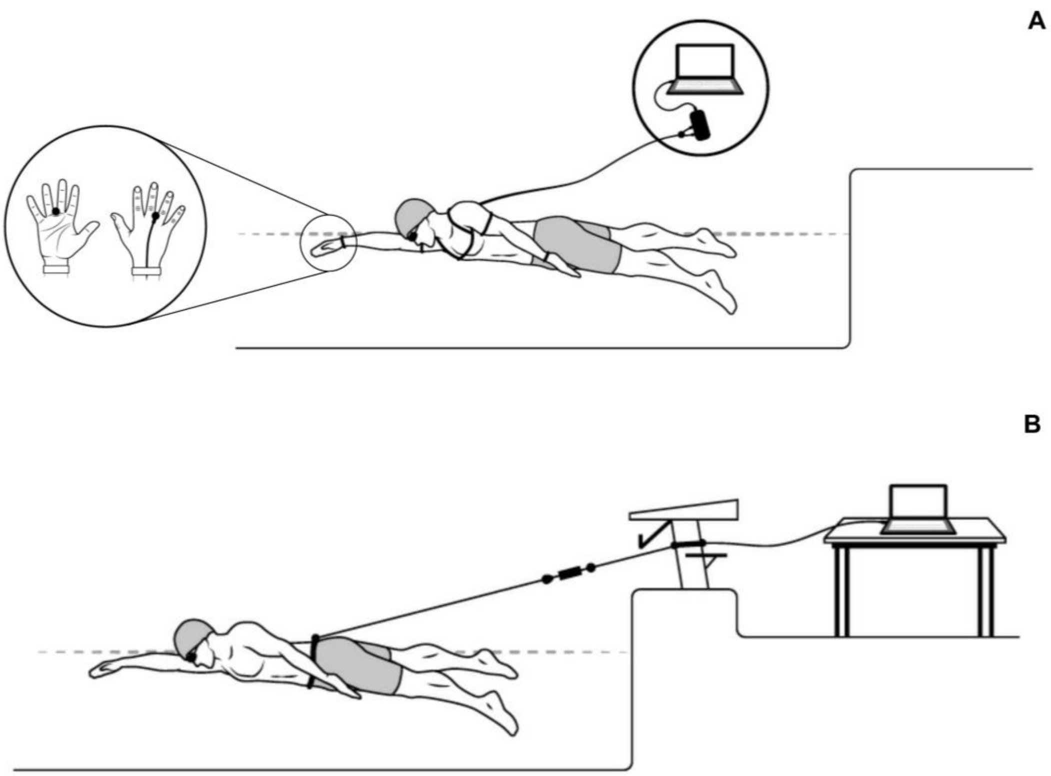

Figure 1. The pressure sensors (Panel A) and tethered swimming (Panel B) tests.

Tethered swimming test

A 30s tethered swimming (full body) was performed at maximum intensity. The swimmers remained connected to a load cell (TS, C2, 300kg, AEP Transducers, Modena, Italy) by means of a steel cable (length: 3.50m) attached to a rigid surface and a belt around their waist (Figure 1, Panel B). The load cell was aligned with the direction of the swim forming an angle of 6º with the water surface. To avoid the inertial effect, participants began the test by swimming for 5s at low intensity before reaching the 30s. A stopwatch (FINIS 3x300, Finis Inc., USA) was used to control the start and end of the test, and an auditory signal was provided for the swimmer. The normal breathing pattern for sprint events was encouraged as the action of breathing does not affect force production in tethered swimming (Psycharakis al., 2021). In addition, the swimmers followed the same order as in the previous session.

Data was acquired with a sampling frequency of 100 Hz using an A/D converter (2mV/V, TAUSB, AEP Transducers, Modena, Italy) connected to a laptop. The calibration of load cell was verified before the test by using specific loads, as reported elsewhere (Amaro et al., 2014).

Force variables

The peak force (F_{PEAK}, in N) of the dominant and non-dominant upper limbs was assessed during the underwater paths for both methods. The F_{PEAK} was defined as the maximum value obtained from the individual force-time curve of three consecutive stroke cycles. The force-time curves retrieved from pressure sensors were analysed between the 11th and 24th meters (Santos et al., 2022b), while for tethered swimming they were considered after the 5s of low intensity (± 6 arm stroke cycles). As swimmers remain stationary in tethered swimming, the first two-stroke cycles were discarded due to the inertial effect. The distance covered by the swimmers with the pressure sensors was recorded using a video camera (Sony, HDR-CX 240, Japan) and a visual mark was applied in the defined interval. For TS, the swimmers were also recorded on video to define which side of the body to begin the test with.

Data from both methods were imported into a signal-processing software (AcqKnowledge v.3.7.3, Biopac Systems, Santa Barbara, CA, USA) and the signal was handled with a 5 Hz cut-off low-pass fourth order Butterworth filter. In addition, further analysis of tethered swimming comprised an angle correction by computing the horizontal component of force (Baratto de Azevedo et al., 2021).

Statistical analysis

The normality and homoscedasticity of the data were verified by the Shapiro-Wilk and Levene's tests, respectively. The mean and one standard deviation (M±1SD) were computed as descriptive statistics. A paired sample t-test was used to compare the variables between both methods, and between measured and predicted values in the selected in-water force variables. Cohen's d was selected as an effect size (d) and interpreted as: trivial if $|d| < 0.2$, medium if $0.2 > |d| < 0.5$, and large if $|d| \geq 0.5$ (Cohen, 1988). Bland-Altman plots with 95% limits of agreement (LoA) were used to display within-subject variation and systematic differences between the two methods. The bias (mean difference), standard deviation (SD), and upper and lower LoA were calculated (Bland and Altman, 1986).

Simple linear regression models between both methods were computed for all variables. As there is still no consensus on the gold standard method for measuring in-water forces, dependent (y-axis) and independent (x-axis) variables were analysed using two approaches: (i) y-axis, tethered-swimming; x-axis, pressure sensors; and (ii) y-axis, pressure sensors; x-axis, tethered-swimming. Scattergrams were included with the main trendline, determination coefficient (R^2), adjusted determination coefficient (R_a^2), and standard error of estimate (SEE). As a rule of thumb, effect sizes were interpreted as: (i) very weak if $R^2 < 0.04$, weak if $0.04 \geq R^2 < 0.16$, moderate if $0.16 \geq R^2 < 0.49$, high if $0.49 \geq R^2 < 0.81$, and very high if $0.81 \geq R^2 < 1.0$ (Barbosa et al., 2015). The trendline equation obtained from the two approaches ($Y = a+bX$) was defined as the Correction Factor.

All statistical analyses were performed using the SPSS software (v.27, IBM, SPSS Inc., Chicago, IL, USA) and GraphPad Prism (v.9, GraphPad Software, San Diego, CA, USA). The statistical significance was set at $p \leq 0.05$.

Results

The descriptive analysis of force variables is shown in Table 2. The comparison between methods revealed significant differences ($p \leq 0.05$) with a large effect in all variables.

Table 2. Descriptive statistics for the selected in-water force variables according to the girls (n=16) and boys (n=15).

Group	Variable	PS (M±1SD)	TS (M±1SD)	Mean difference (95CI)	t-test (*p*)	*d*
Girls	F_{PEAK} D (N)	57.28±11.26	103.17±19.79	-45.89 (-55.08 to -36.70)	-10.64 (<0.001)	2.92
	F_{PEAK} ND (N)	55.67±14.35	99.46±20.56	-43.79 (-52.25 to -35.32)	-11.02 (<0.001)	2.53
Boys	F_{PEAK} D (N)	60.78±15.31	128.04±35.28	-67.26 (-81.58 to -52.95)	-10.08 (<0.001)	2.56
	F_{PEAK} ND (N)	61.56±19.95	123.34±36.02	-61.78 (-76.99 to -46.56)	- 8.71 (<0.001)	2.20

95CI, 95% confidence interval; d, Cohen's d; F_{PEAK}, peak force; N, Newton; PS, pressure sensors; TS, tethered-swimming; (-), TS presents higher values than PS.

The Bland-Altman plots are presented in Figure 2. Biases (mean differences) were large for dominant and non-dominant limbs in girls (Panel A and Panel B) and boys (Panel C and Panel D). Visual inspection of the plots revealed that most data points were within the LoA for all variables.

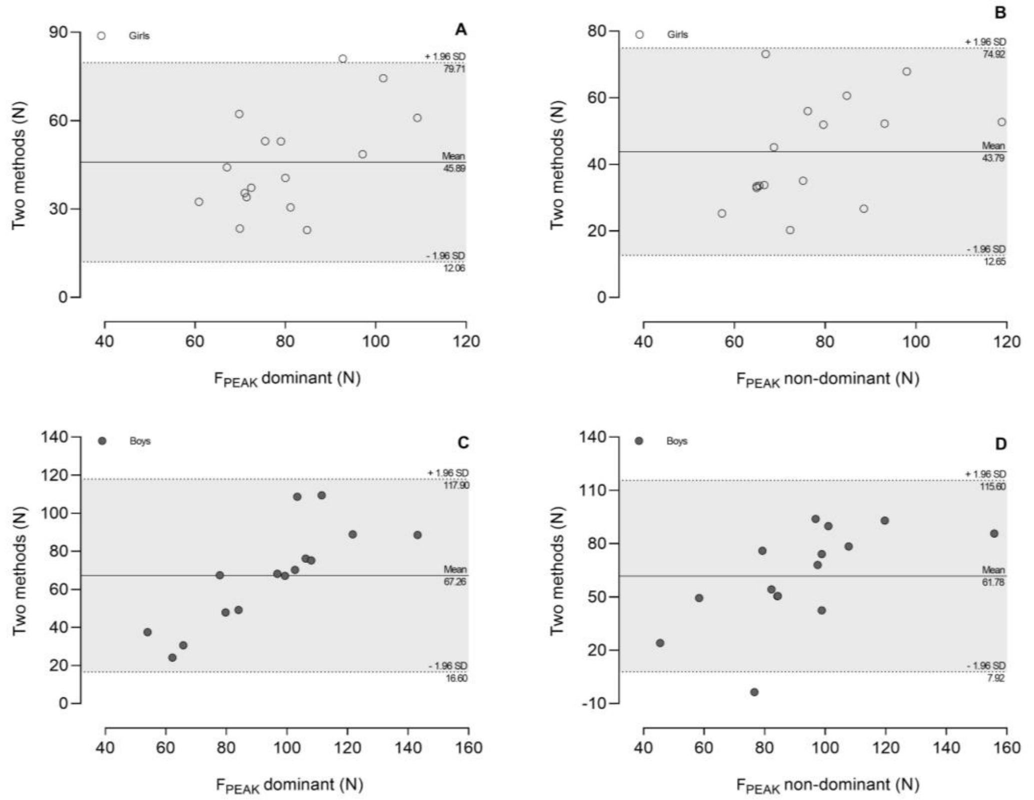

Figure 2. Bland-Altman plots of the difference between PS and TS (y-axis) and mean of measurements (x-axis) for all variables. Dotted lines represent the upper and lower 95% LoA (mean differences ± 1.96 SD of the differences) and solid lines represent the mean differences between the two methods (bias). N, Newton; F_{PEAK}, peak force.

Simple linear regression models (Figure 3) showed significant relationships in girls (F_{PEAK} dominant, p=0.051; F_{PEAK} non-dominant, p=0.008) and boys (F_{PEAK} dominant, p=0.001; F_{PEAK} non-dominant, p=0.008). A moderate effect was found in all variables for girls, while in boys a high and moderate effect was verified for F_{PEAK} of dominant and non-dominant limbs (respectively). From the trendline equations, correction factors were obtained (Table 3). No differences were found between the measured values (Table 2) and the estimated values for girls and boys.

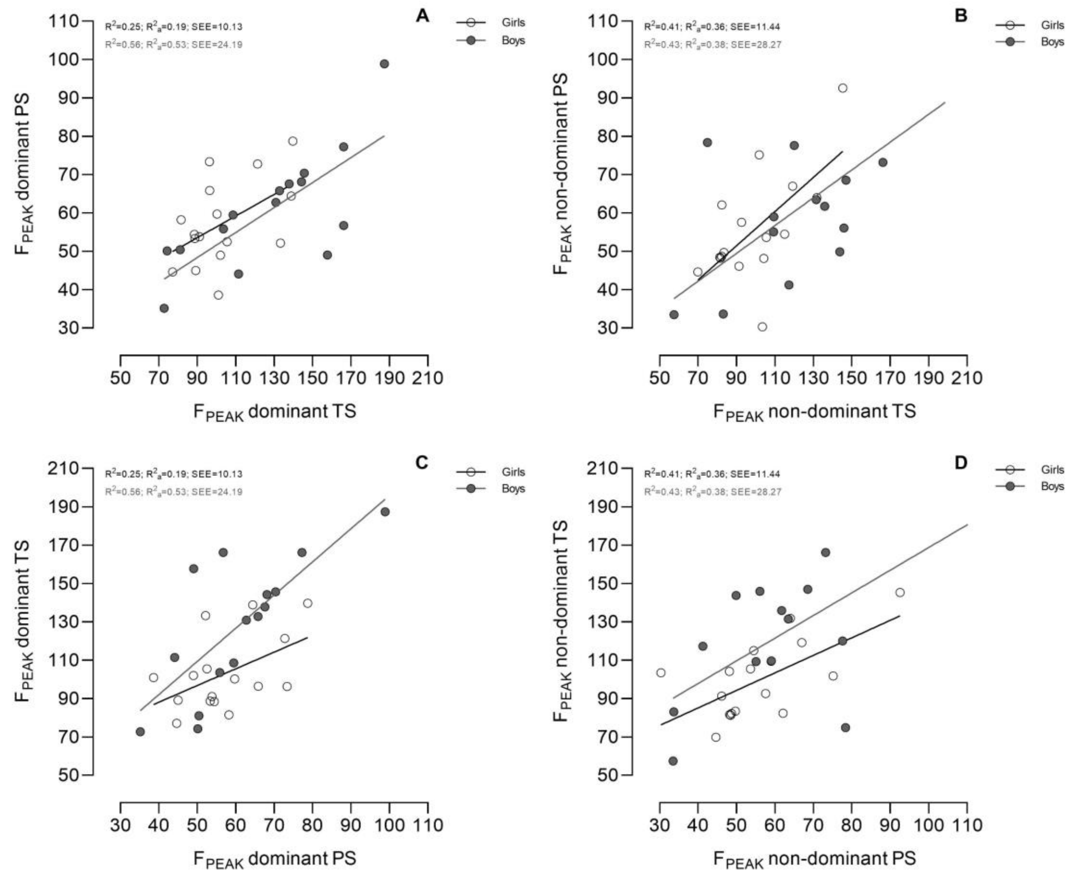

Figure 3. Scattergrams with the main trendline, determination coefficient (R^2), adjusted determination coefficient (R_a^2), and standard error of estimate (SEE). Black trendlines or white dots represent girls, and light grey trendlines or filled dots represent boys. N, Newton; F_{PEAK}, peak force; PS, pressure sensors; TS, tethered-swimming.

Table 3. Correction Factor for the selected in-water force variables.

Group	Predictor variable	Correction Factor
Girls	F_{PEAK} dominant PS (N)	= 0.2817 · FPEAK dominant TS + 28.22
	F_{PEAK} non-dominant PS (N)	= 0.4451 · FPEAK non-dominant TS + 11.40
	F_{PEAK} dominant TS (N)	= 0.8697 · FPEAK dominant PS + 53.35
	F_{PEAK} non-dominant TS (N)	= 0.9133 · FPEAK non-dominant PS + 48.61
Boys	F_{PEAK} dominant PS (N)	= 0.3257 · FPEAK dominant TS + 19.07
	F_{PEAK} non-dominant PS (N)	= 0.3624 · FPEAK non-dominant TS + 16.86
	F_{PEAK} dominant TS (N)	= 1.7300 · FPEAK dominant PS + 22.92
	F_{PEAK} non-dominant TS (N)	= 1.1810 · FPEAK non-dominant PS + 50.64

N, Newton; F_{PEAK}, peak force; PS, pressure sensors; TS, tethered-swimming.

Discussion and Implications

The main finding of the present study was that the peak force measured by tethered swimming and pressure sensors differ significantly. These results confirm the established hypothesis, as large biases were found in all force variables for girls and boys. Thus, a correction factor was developed to make it comparable.

The upper limbs play an important role in swimming propulsion during front crawl (Deschodt et al., 1999), mainly due to the trajectory and orientation of the swimmer's hand. Due to the complexity of unsteady flow mechanics in human swimming, available methods to directly measure in-water force are scarce. Some advances in technology led to a regular and systematically use of tethered swimming and pressure sensors to control these forces (Santos et al., 2021). Still, there is a paucity of information on how the data from both methods can be comparable.

The results of the present study showed F_{PEAK} values similar to those previously reported (Santos et al., 2021). For instance, Santos et al. (2022b) reported values using pressure sensors of ≈50 N in young competitive swimmers (12.38±0.48 years), while an F_{PEAK} of 20.2 kgf (≈198 N) was found for young girls (12.50±1.80 years) in tethered swimming (Oliveira et al., 2021). It is noteworthy that most of the available studies included swimmers over 15 years of age (Santos et al., 2021), therefore, higher F_{PEAK} values were shown compared to those in this study.

The mean differences in this study were around ≈46 N and ≈67 N in girls and boys (respectively) when both methods were compared. As far as our understanding goes, only one study attempted a similar approach (Löppönen et al., 2022). The authors aimed to compare a load cell with a commercial paddle (9-axis IMU plus 1 pressure sensor) to measure the in-water forces of paddle stroke in canoe polo. The same authors found that the paddles used overestimated the F_{PEAK} compared to the load cell (mean difference of 26.8 N), arguing that the differences might be due to data filtering. Despite this, the results of the present study showed a higher F_{PEAK} for tethered swimming (i.e., load cell) when compared to pressure sensors. Again, these differences seem to exist due to the "nature" of the assessments. Tethered swimming requires a fixed position, but it is essential to ensure that the cable remains taut. Even so, a gap in the period of time between propulsive phases of dominant and non-dominant upper or lower limbs can lead to backward acceleration due to the loss of cable tension (Takagi et al., 2021). Thus, the swimmer will need to re-tension the cable, which can lead to an overestimation of the F_{PEAK}. The absence of drag force acting on the swimmers can also impact the force data (Barbosa et al., 2020). The lack of fluid flow at a certain speed supports the idea that tethered swimming measures muscle strength potential rather than the force actually applied (Ruiz-Navarro et al., 2020). As testing in-water should resemble the "free swimming" actions (i.e., ecologically valid environment) as closely as possible, interest in the use of sensors is increasing (Santos et al., 2021). The absence of a gold standard method to measure these forces does not allow a deeper understanding of propulsion mechanics in water. Thus, the use of correction factors can help researchers and coaches to compare data between methods, at least if they use tethered swimming or pressure sensors (i.e., Aquanex System).

The methodology for comparing and providing correction factors for force estimation is not new to the sports sciences (e.g., Forte et al., 2020). Some of them were proposed to make the data comparable in competitive swimming (e.g., Barbosa et al., 2015). Again, this is the first study that provides a correction factor to compare methods that measure forces (i.e., acting on the direction of the displacement) in swimmers. Although there was a significant relationship between the methods, a bias existed, and a correction factor has been applied to all variables. The accuracy of the predictions in girls was around 11 N for both limbs, while in boys was from 24 N to 28 N. A previous study conducted with experimental and analytical procedures to measure passive drag in swimming also found a SEE near to 11 N (Barbosa et al., 2015). When analytical procedures were compared with the numerical simulations (CFD; Barbosa et al., 2018) values presented a lower error (SEE=5.40 N). So, we may argue that our values are not so far from the ones reported in the same context.

It is also worth mentioning that SEE fitted better for girls than for boys. Despite the chronological age of the swimmers being the same, the variation between the swimmers may explain some bias in the data, as at this stage they are susceptible to the biological maturation process (Dos Santos et al., 2021). Finally, some limitations of the study are worth mentioning: (i) only young swimmers were considered; it is expected that the performance variability in young swimmers will be greater than their adult counterparts; (ii) only one swimming stroke and condition (full stroke) were assessed; and (iii) the pressure sensors were placed in the hands only. However, it is important to highlight that the present study allows, for the first time, the estimate of F_{PEAK} with PS or TS, enabling the swimming community to easily obtain precise and accurate data through different methods.

Conclusion

The in-water force values in young competitive swimmers rely on different assessment methods. Based on the general findings, tethered swimming presents higher values when compared to pressure sensors. To provide insightful benchmarks on swimmers' progression by monitoring training, correction factors can be used when different methods are considered.

Study 3. Reliability of using a pressure sensor system to measure in-water force in young competitive swimmers

Abstract

The aim of this study was to analyze the reliability of using a differential pressure system to measure in-water force in young competitive swimmers. Ten boys and five girls (12.38 ± 0.48 years, 49.13 ± 6.82 kg, 159.71 ± 7.99 cm) were randomly assigned to perform two maximum bouts of 25 m front crawl on different days (trial one, T1; trial two, T2), one week apart. A differential pressure system composed of two hand sensors (Aquanex System, v.4.1, Model DU2, Type A, Swimming Technology Research, Richmond, VA, United States) was used to measure the peak (RF_{PEAK}) and the mean (RF_{MEAN}) resultant force of the dominant and non-dominant hands (in Newton, N). Reliability was analyzed by computing the intraclass correlation coefficient (ICC), typical error (TE), smallest worthwhile change (SWC), coefficient of variation (CV%), standard error of measurement (SEM), and the minimal detectable change (MDC). Bland–Altman plots with 95% limits of agreement were also analyzed. The results showed no differences between T1 and T2 in all variables ($p > 0.05$). The ICC showed "excellent" reliability (ICC > 0.90) for the RF_{PEAK} and RF_{MEAN} in both hands. The CV% was rated as "good" (<5%) and TE was smaller than SWC in all variables. The Bland-Altman plots showed high reliability with a small bias (RF_{PEAK} dominant, -0.29 N; RF_{PEAK} non-dominant, -0.83 N; RF_{MEAN} dominant, 0.03 N; RF_{MEAN} non-dominant, 0.50 N). The pressure sensor system (Aquanex System) seems to be a reliable device for measuring the hand resultant force during front crawl in young swimmers and can be used to monitor the changes over time.

Key words: swimming; kinetics; differential pressure; accuracy; hand force

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Introduction

Deterministic models of swimming performance have highlighted kinetics as an important domain to be studied (T. M. Barbosa et al., 2013). The ability of swimmers to move through the water depends on the amount of propulsive force applied and the drag force opposed to a forward motion. With that in mind, individual force profiles were used to understand propulsive mechanics in the water (Santos et al., 2021).

In the last couple of years, some progress has been made on how propulsive forces are retrieved (Santos et al., 2021). Methods with humans or robotic models based on numerical simulations (e.g., Marinho et al., 2010) or tethered swimming (e.g., Amaro et al., 2014) were used for that purpose; but those kind of approaches were quite heavy to handle or too much time consuming. Thus, the use of differential pressure sensors has been growing in interest. The method of assessing pressures differences between the palmar and dorsal surfaces, along with underwater motion analysis, allows to estimate the propulsive forces (Takagi & Wilson, 1999) and interpret those possible effects on performance (Tsunokawa et al., 2018; Koga et al., 2022). This straightforward method allows the assessment of swimmers in a more ecologically valid environment (i.e., similar to "free-swimming").

Studies using the differential pressure method reported the measurement of in-water forces using two (e.g., Pereira et al., 2015; Bartolomeu et al., 2022) or four to eight sensors (e.g., Takagi & Wilson, 1999; Koga et al., 2020) in swimming strokes. Despite the number of sensors in play, the Aquanex System (a two-hand set-up) showed to be an easy-to-use procedure without encompassing a heavy set-up. This is an important advantage of the system when compared to other differential pressure sensors reported in the swimming science literature (e.g., Takagi & Wilson, 1999; Tsunokawa et al., 2018; Koga et al., 2022). Still, should point out that each sensor only measures the hand resultant force instead of the effective propulsive force. Although some studies reported the use of Aquanex System, the system accuracy and the reliability of the measurements has not yet been investigated. Meanwhile, young swimmers seem not to be constrained in stroke mechanics or stroke efficiency when using this system (Santos et al., 2022).

The peak and mean forces retrieved by this pressure sensors system have been regularly used to understand acute responses to different stimulus (e.g., Morais et al., 2020), the relationship to swimming velocities (e.g., Bartolomeu et al., 2022), upper-limb imbalances (e.g., Morais et al., 2020), or warm-up effects (e.g., T. M. Barbosa et al., 2020). Both kinetic variables appear to be highly reliable in young swimmers when using the tethered- swimming method (Amaro et al., 2014). However, it is still unclear whether the same happens when a pressure system with two hand sensors is used for this purpose. Thus, ensuring the reliability of the Aquanex System would help researchers and practitioners to perform a proper assessment over time and monitoring swimmers' progress.

The aim of this study was to analyze the reliability of using a differential pressure system to measure in-water force during front crawl in young competitive swimmers. It was hypothesized that pressure sensors would present excellent reliability to measure the peak and the mean of hand resultant force.

Materials and Methods

Participants

Fifteen highly trained (Mckay et al., 2022) swimmers including 10 boys and 5 girls [mean ± one standard deviation: 12.38 ± 0.48 years old, 49.13 ± 6.82 kg, 159.71 ± 7.99 cm, 309.17 ± 58.13 FINA Points at 50-m freestyle (short course)] volunteered to participate in this study. Swimmers were recruited from a local swimming squad and assessed at the end of the first macrocycle (peak form). The inclusion criteria were defined as follows: 1) having a minimum of two years in competitive swimming in regional or national events; 2) practicing more than four swim training sessions per week; 3) being previously familiar with the hand differential pressure system; and 4) not having suffered any injuries in the past 6 months.

Swimmers' parents or guardians were informed about the benefits and experimental risks before signing a written informed consent form. All procedures were in accordance with the Declaration of Helsinki and approved by the Institutional Ethics Committee of the University of Beira Interior (code: CE-UBI-Pj-2020-058).

Data collection

A single group repeated measures design was selected for this study. The in-water experimental testing was carried out in a 25 m indoor swimming pool (water temperature: 27.5°C) and the swimmers attended two sessions on different days, 1 week apart. A standardized 1000 m warm-up for sprint events (Neiva et al., 2015) was performed individually by each swimmer. For the in- water data collection, swimmers were randomly assigned for the first maximum bout of 25 m front crawl (Trial 1, T1) and followed the same order in the second session (Trial 2, T2). All maximum bouts started by a push-off without gliding and swimmers were instructed to maintain their normal breathing pattern for sprint events.

Swimmers wore only a textile swimsuit and a cap during the anthropometric tests. Height (in cm) and body mass were measured with a digital stadiometer (SECA, 242, Hamburg, Germany) and a scale (TANITA, BC-730, Amsterdam, Netherlands), respectively. Hand dominance of the swimmers was assessed by self-report.

Pressure sensors test

A differential pressure system composed of two hand sensors (Type A, Swimming Technology Research, Richmond, VA, United States) positioned between the third and fourth proximal phalanges and metacarpals was used to measure the pressure between the palmar and dorsal surfaces of both hands. Inside each sensor, there is a diaphragm that flexes and is sensed as an electrical signal that is proportional to the difference in the two pressures. Each sensor measures the pressure component acting perpendicular to it. The hand resultant force (in N) was derived by the system from the product of differential pressure by the hand surface area of each swimmer (i.e., differential pressure · hand surface). The sensors (3.18 cm × 1.91 cm x 2.54 cm; 0.226 kg) were attached by a cable (15 m of length) to a two channel A/D interface connected to a laptop with the Aquanex software (v.4.1, Model DU2, Swimming Technology Research, Richmond, VA, United States). Swimmers carried the system with shoulders and arms elastic straps. An illustration of the experimental set-up can be found in Santos et al. (2022). Before each bout, swimmers kept their hands immersed (10 s) at the waistline to calibrate the system with the hydrostatic pressure values. Data was acquired with a sampling frequency of 100 Hz for each maximum bout.

Data analysis

Data was imported into a signal-processing software (AcqKnowledge v.3.7.3, Biopac Systems, Santa Barbara, CA, United States) and the signal was handled with a 5 Hz cutoff low-pass fourth order Butterworth filter. The peak (RF_{PEAK}, in N) and the mean (RF_{MEAN}, in N) resultant force of the dominant and non-dominant hands were assessed during the underwater paths. The recovery phase was discarded for all cycles The RF_{PEAK} was defined as the maximum value achieved on the three consecutive stroke cycles analyzed between the 11th and 24th meter, as suggested elsewhere (Santos et al., 2022). The distance covered by the swimmers was recorded (Sony, HDR-CX 240, Japan) and a visual mark was applied in the defined interval. The RF_{MEAN} was defined as the mean of the values obtained from the force-time curve where the RF_{PEAK} was retrieved.

Statistical analysis

The normality and homoscedasticity of the data were checked using the Shapiro-Wilk and Levene tests, respectively. The mean and one standard deviation (M±1SD) were computed as descriptive statistics. A paired sample t-test was used to compare the outcome variables between the T1 and T2. Relative test-retest reliability of each variable was assessed using the intraclass correlation coefficient (ICC) plus 95% confidence intervals (95%CI) with two-way mixed effects model (absolute agreement, single measures). The ICC was classified as poor if ICC < 0.50, moderate if 0.50 ≥ ICC < 0.75, good if 0.75 ≥ ICC < 0.90, and excellent if ICC > 0.90 (Koo & Li, 2016). The absolute test-retest reliability was analyzed by estimating the typical error (TE), coefficient of variation (CV%), standard error of measurement (SEM), and the minimal detectable change (MDC) based on a 95% confidence level (Atkinson & Nevill, 1998) The CV% values were interpreted as poor if CV% > 10%, moderate if 5% ≥ CV% ≤ 10%, and good if CV% <5% (Scott et al., 2016). Additionally, the ability to detect a change was rated as "good", "OK", or "marginal" when the TE was below, similar, or higher than the smallest worthwhile change (SWC), respectively (Buchheit et al., 2011). Bland–Altman plots with 95% limits of agreement (LoA) were used to display the within-subject variation and systematic differences between the two sessions trials. The bias (mean difference), standard deviation (SD), and upper and lower LoA were calculated (Bland & Altman, 1986).

All statistical analyses were performed in the SPSS software (v.27, IBM, SPSS Inc., Chicago, IL, United States) and GraphPad Prism (v.9, GraphPad Software, San Diego, CA, United States). The statistical significance was set at p ≤ 0.05.

Results

Test-retest reliability of the Aquanex System is shown in Table 1. No differences were found between T1 and T2 in all propulsive force variables. The ICC showed an "excellent" relative reliability for the RF_{PEAK} and RF_{MEAN} in both upper limbs, despite the 95%CI (i.e., lower and upper bound) of ICC demonstrating a "good" to "excellent" relative reliability. TE was rated as "good" when compared to the SWC and CV% revealed a "good" absolute reliability in all variables.

Table 1. Test-retest reliability of the Aquanex System in young competitive swimmers.

Variable	T1 (M±1SD)	T2 (M±1SD)	*p*	TE	SWC	CV%	ICC	$ICC_{95\%CI}$	SEM	MDC
RF_{PEAK} D (N)	50.02±7.81	50.31±8.29	0.65	0.96	1.61	2.70	0.96	0.88, 0.99	1.67	4.63
RF_{PEAK} ND (N)	49.85±10.10	50.68±9.87	0.17	0.99	1.99	2.95	0.97	0.92, 0.99	1.64	4.55
RF_{MEAN} D (N)	16.54±3.49	16.51±3.34	0.93	0.47	0.68	4.30	0.95	0.86, 0.98	0.75	2.07
RF_{MEAN} ND (N)	16.92±3.44	16.42±3.79	0.19	0.56	0.71	4.64	0.92	0.79, 0.97	1.00	2.76

D, dominant hand; CI, confident interval; CV%, coefficient of variation in percentage; ICC, intraclass correlation coefficient; $ICC_{95\%CI}$, lower and upper bound of ICC; MDC, minimal detectable change; N, Newton; ND, non-dominant hand; RF_{PEAK}, peak resultant force; RF_{MEAN}, mean resultant force; SEM, standard error of measurement; SWC, smallest worthwhile change; T1, trial 1; T2, trial 2; TE, typical error.

The Bland-Altman plots are presented in Figure 1. Biases (mean differences) were small, approaching zero, and most data points were within the LoA on all resultant force variables.

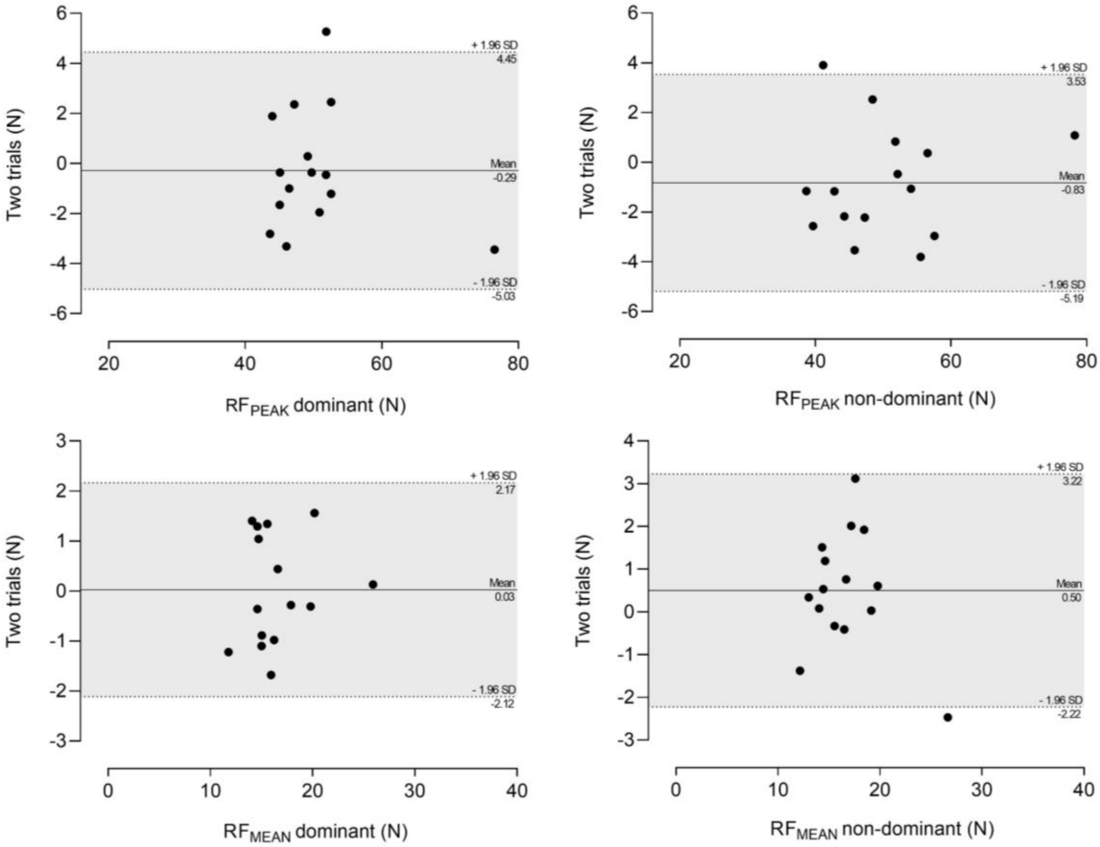

Figure 1. Bland-Altman plots of the difference between T1 and T2 (y-axis) and mean of measurements (x-axis) for all variables. Dotted lines represent the upper and lower 95% LoA (mean differences ± 1.96 SD of the differences) and solid lines represent the mean differences between the two trials (bias). N, Newton; RF_{PEAK}, peak resultant force; RF_{MEAN}, mean resultant force.

Discussion

This study analyzed the reliability of using a differential pressure system to measure the hand resultant force during front crawl in young competitive swimmers. The main results show that the pressure sensor system has excellent reliability through the measurement of peak and mean resultant force.

Previous studies using the Aquanex system determined the peak and the mean as the most frequent variables to be studied (Santos et al., 2021). Our results showed values of ≈50 N for RF_{PEAK} and ≈17 N for RF_{MEAN}. These values are lower than previous findings in front crawl stroke, but the age range reported was different from those used in the present study (e.g., T. M. Barbosa et al., 2020; Morais et al., 2020). Furthermore, studies reporting hand resultant force with multi-pressure system also found higher values (e.g., Tsunokawa et al., 2018; Koga et al., 2022).

The reliability of different devices/apparatus in swimming has been extensively investigated. Inertial measurement units (IMU) to assess in-water kinematics (Mooney et al., 2015) and dynamometers for dry-land strength assessment (e.g., Conceição et al., 2018) have already been tested. As far as we know, the reliability of devices to directly measure in-water forces have only been done using the tethered swimming method (Amaro et al., 2014; Nagle Zera et al., 2021). Hence, this study is the first to provide data about test-retest reliability with hand pressure sensors.

The ICC values observed in the present study were classified as "excellent" (range: 0.92–0.97) in both variables for the dominant and non-dominant hands. These results are in agreement with those observed in front-crawl in tethered swimming (Amaro et al., 2014; A. C. Barbosa et al., 2020; Dos Santos et al., 2017; Loturco et al., 2015; Morouço et al., 2014). For instance, Amaro et al. (2014) reported high reliability for peak (ICC: 0.94) and mean forces (ICC: 0.96) in young swimmers. Although tethered swimming is considered a reliable apparatus, some concerns have been raised as swimmers remain in stationary conditions with no forward motion (Soncin et al., 2017). Furthermore, it is expected that with such method swimmer's hand would experience much larger pressure than in a free-swimming condition. On the other hand, the pressure sensors allow a displacement throughout the water without mechanical and efficiency constraints in young swimmers (Santos et al., 2022).

Although the reliability of the two pressure sensors has not been investigated in previous studies, Havriluk (1988), who introduced the first version of the Aquanex System, reported an ICC value of 0.91 for the variable "effective hand movement with respect to the body" (in m). Nevertheless, in-water force values were not analyzed, therefore, no conclusions were drawn about reliability.

The absolute reliability demonstrated a "good" CV% without systematic changes between trials. The CV% ranged from 2.70 to 4.64% and the TE was below 1N being rated as "good" when compared to the SWC. The SEM was less than 2N in all variables. Thus, the differential pressure system (Aquanex System) might be a reliable apparatus to monitor changes in hand resultant force over the season. Meanwhile, different CV% values have been reported for tethered swimming, being lower (A. C. Barbosa et al., 2020; Loturco et al., 2015) or higher (Amaro et al., 2014) than those found in the present study. Different settings, such as the competitive level of the sample, swimmers' age, or data analysis, can help explain these differences.

Some limitations can be addressed: 1) equal pressure assumption on the hand surface, although it has been shown that the pressure is not the same across the whole surface of the hand; 2) only the resultant force was considered; 3) only the reliability of the hands was considered, although the in-water forces of the feet's has also been investigated through pressure sensors. Thus, testing its reliability alone or using the set-up of the hand should be a priority in the future; 4) only peak and mean forces of young swimmers were considered; the use of other measures (e.g., impulse) and type of swimmers (e.g., elite or master) would be essential; and 5) front-crawl is not representative of all swimming strokes, so future studies should try to understand whether systematic changes are the same for butterfly, backstroke, and breaststroke.

Conclusion

The pressure sensor system (Aquanex System) can be considered a reliable set-up to obtain peak and mean hand resultant force in young competitive swimmers. This reinforces the idea that the use of pressure sensors remains the assessment method that most closely resembles free- swimming and can be used to monitor kinetic changes over time.

Study 4. The mechanical and efficiency constraints when swimming front crawl with the Aquanex System

Abstract

The aim of this study was to compare the mechanical and efficiency constraints between free swim and swimming with differential pressure sensors (Aquanex System). These conditions were also analysed to understand the differences between sexes. Thirty young swimmers, 14 boys and 16 girls (12.31 ± 0.67 years) performed three 25-m front crawl maximal bouts under each condition: free swim and swimming with sensors. Under the condition with sensors, swimmers carried the Aquanex System composed of two hand pressure sensors (v.4.1, Model DU2, Type A, Swimming Technology Research, Richmond, VA, USA). The 25-m time (T25) was assessed as a swimming performance variable. The swimming velocity (v), stroke rate (SR), and stroke length (SL) were assessed and calculated as stroke mechanics variables. Thereafter, the stroke index (SI) and arm stroke efficiency (ηF) were estimated for swimming efficiency. Statistical significance was set at $p \leq 0.05$. Swimming performance was impaired when swimmers swam with sensors (overall: $p = 0.03$, $d = 0.14$; $\Delta = 1.30\%$) and a significant decrease in v was found for overall ($p = 0.04$, $d = 0.14$; $\Delta = 1.42\%$) and the girls' group ($p < 0.01$, $d = 0.39$; $\Delta = -1.99\%$). The remaining stroke mechanics variables showed no differences between conditions, as well as for swimming efficiency. Furthermore, there were no differences between girls and boys in free swim and with sensors for all variables. Swimming with the Aquanex System seems not to impose constraints in the mechanics and efficiency of young swimmers, despite differences in swimming performance and v.

Key words: propulsive force; direct method; pressure sensors; kinematic; gender; training.

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Introduction

The main goal of human competitive swimming is to diminish drag and increase propulsion to achieve a higher swim velocity and, therefore, travel a given distance in the shortest possible time. In this context, an in-depth analysis of key variables is performed regularly to advise swimmers about ways to progress (Barbosa et al., 2021). In the last couple of decades, there has been a boost in technological advances to get a more friendly and ecological assessment in the water. A large set of devices was developed in a diversity of areas, which allowed researchers to carry out a proper assessment of the various factors that influence swimming performance.

One of the recent areas of scientific research includes swimming kinetics (Santos et al., 2021). The ability to produce propulsive force in the water has been a topic of great interest. A differential pressure sensors system (Aquanex System, Swimming Technology Research) was designed to measure swimmers' propulsive force. This is a user-friendly set-up that allows the swimmer's displacement throughout the water in a very similar condition to "free swimming" and delivers real-time feedback (Santos et al., 2021). This commercially available hydrodynamic system palmar/plantar and dorsal surface (Barbosa et al., 2020) of each body limb (i.e., hands and feet), and hence provides force output (N, newton) as the product of pressure and the area.

Previous studies used the Aquanex System to understand the behaviour of propulsive forces generated by the upper and lower limbs during front-crawl (e.g., Barbosa et al., 2020; Morais et al., 2020; Ng et al., 2019) and the butterfly stroke (e.g., Morais et al., 2021; Pereira et al., 2015). Some of them also reported the assessment of kinematic variables while propulsive force was retrieved (e.g., Morais et al., 2021). Although considered accurate, carrying these tiny pressure sensors can impose some mechanical constraints leading to an underestimation or overestimation of kinematic and efficiency data. Since the change of the hand area surface can occur from additional body salience promoted by the sensors, resistive forces, such as pressure drag, can increase and affect arm stroke motion.

The constraints imposed by several devices during underwater testing have already been a topic of interest. Slight changes in the biomechanical pattern have been found when swimmers used the AquaTrainer® snorkel for physiological purposes (Barbosa et al., 2010; Conceição et al., 2013; Ribeiro et al., 2016; Szczepan et al., 2018). However, to date, there is no evidence of whether the Aquanex System impairs the swimming pattern, and what are the constraints derived from using it. This kind of feedback will help researchers and coaches to be comfortable when using this system in their daily tasks.

The aim of this study was twofold: (i) to analyse and compare the mechanical and efficiency constraints between free swim and the Aquanex System; and (ii) to understand if there are differences in response between sexes. It was hypothesised that: (i) swimming with the Aquanex System would impose slight constraints in the front crawl; and (ii) boys and girls would show similar constraints while using the device.

Materials and Methods

Participants

Thirty young swimmers (14 boys and 16 girls) were recruited to participate in this study (Table 1). Swimmers were assessed at the end of the third macrocycle (peak form) and the inclusion criteria consisted of: (i) being a competitive swimmer; (ii) having at least two years of experience competing in regional or national events; (iii) completing more than four swim training sessions per week; and (iv) not having suffered from any injury in the past six months. Swimmers' parents or legal guardians were informed about the benefits and experimental risks before signing a written informed consent form. All procedures were in accordance with the Declaration of Helsinki and approved by the Institutional Ethics Committee of the University of Beira Interior (code: CE-UBI-Pj-2020-058).

Table 1. Demographics of the competitive swimmers.

	Overall (n=30) M±1SD	Boys (n=14) M±1SD	Girls (n=16) M±1SD
Age (years)	12.31±0.67	12.58±0.64	12.07±0.59
Body mass (kg)	48.53±8.43	50.75±7.57	46.62±8.65
Height (cm)	157.54±7.48	159.63±8.38	155.76±6.06
Arm span (cm)	158.05±8.34	160.82±9.67	155.68±6.06
Dominant upper-limb (cm)	71.02±4.18	72.53±4.54	69.73±3.33
FINA points (50-m freestyle)	270.17±62.27	278.30±75.06	263.92±49.35

kg, kilogram; cm, centimeter.

Procedures

The in-water testing took place in a 25-m indoor swimming pool (mean water temperature: 27.5°C) during two consecutive days (24 h apart) in the afternoon period. Swimmers were randomly assigned (first bout) to perform 25-m all-out sprints in front crawl (full stroke), after a standard warm-up previously reported for sprinting events (Neiva et al., 2015). Each swimmer undertook three maximal bouts per each selected condition on separate days: free swim and swimming with sensors. All in-water bouts started by a push-off and swimmers were instructed to maintain their normal breathing pattern for sprinting events. To ensure full recovery, a 30-min rest interval between bouts was applied. All swimmers were encouraged to avoid intense exercise on the data collection days, as well as the day before. The in-water data were assessed in all bouts for both conditions and the best result was considered for further analysis. Under the condition with sensors, swimmers wore a differential pressure system composed of two hand pressure sensors (Type A, Swimming Technology Research, Richmond, VA, USA) positioned between the third and fourth metacarpals (Figure 1).

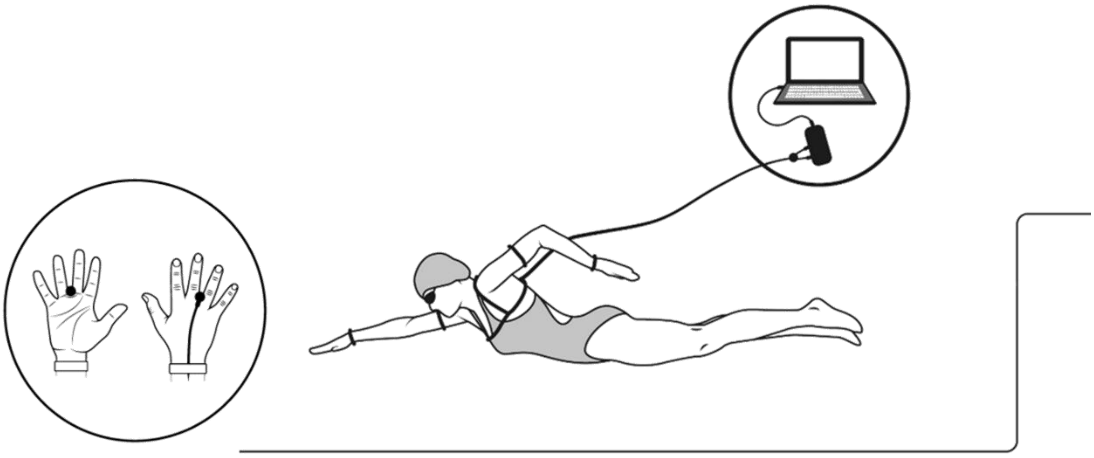

Figure 1. Swimmer carrying the hand differential pressure system with the Type A sensors.

The shoulders and arms elastic straps allowed the system to be carried during the swimmer's displacement throughout the water and the sensors were connected to an interface connected to a laptop with Aquanex software (v.4.1, Model DU2, Swimming Technology Research, Richmond, VA, USA). The time spent (in s) to cover the predefined distance (i.e., 25 m) was manually assessed by two experts (ICC: 0.97), each with a stopwatch (FINIS 3x100, Finis Inc., USA), and it was considered as a swimming performance variable (T25). The stroke mechanics comprised the swimming velocity (swimming v), the stroke rate (SR), and the stroke length (SL). The v (in $m \cdot s^{-1}$) was calculated based on the ratio between the distance and T25. The SR (in Hz) was assessed with a chrono-frequency meter (FINIS 3x300, Finis Inc., USA) from three consecutive stroke cycles between the 11th and the 24th m, and the SL (in m) was estimated ($SL = v / SR$) as reported elsewhere (Costa et al., 2020; Craig & Pendergast, 1979). To analyse swimming stroke efficiency, the stroke index (SI, in $m^2 \cdot s^{-1}$) was computed ($SI = v \cdot SL$) (Costill et al., 1985), and the arm stroke efficiency (ηF, in %), based on Froude efficiency, was estimated as (1):

$$\eta F: (([v \cdot 0.9] / [2\pi \cdot SF \cdot l]) \cdot (2 / 2\pi)) \quad (1)$$

in which l is the arm's length (in m) computed as Zamparo et al. (2005) reported.

Statistical analysis

The normality of the data distribution was checked with the Shapiro-Wilk test. The mean and one standard deviation (M±1SD) were computed for all variables, as well as the mean percentage of change (Δ). The dataset for each condition was split into three groups: overall (n = 30), boys (n = 14), and girls (n = 16). The paired sample t-test was used to compare both conditions in all variables, whereas the unpaired t-test was used to verify the differences between genders (i.e., boys and girls). Cohen's d was selected as an effect size (d) and interpreted as: trivial if $|d| < 0.2$, medium if $0.2 > |d| < 0.5$, and large if $|d| \geq 0.5$ (Cohen, 1988). All statistical analyses were performed in SPSS software (v.27, IBM, SPSS Inc., Chicago, IL, USA) and GraphPad Prism (v.9, GraphPad Software, San Diego, CA, USA). The statistical significance was set at $p \leq 0.05$.

Results

The comparison of swimming performance under both conditions is shown in Figure 2. Overall, there was an increase in T25 when swimming with sensors ($p = 0.03$, $d = 0.14$; $\Delta = 1.30\%$), despite the trivial difference. While boys had similar T25 under both conditions ($p = 0.51$, $d = 0.05$; $\Delta = 0.61\%$), girls presented a significant and medium difference ($p < 0.01$, $d = 0.35$; $\Delta = 1.90\%$). The unpaired t-test revealed no differences between sexes in T25.

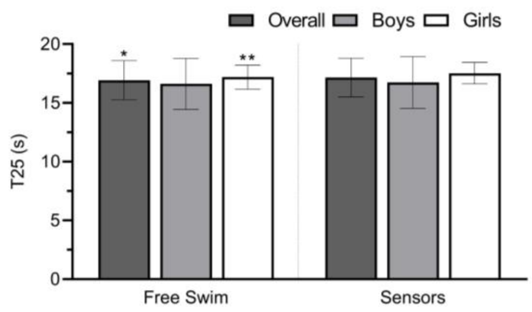

Figure 2. Comparison of swimming performance between free swim and sensors at front crawl. *p ≤ 0.05 or **p ≤ 0.01, denotes a significant difference to sensors.

Figure 3 depicts the comparison between free swim and swimming with sensors according to the stroke mechanics variables. The v (Panel A) achieved overall presented a significant although trivial difference ($p = 0.04$, $d = 0.14$; $\Delta = 1.42\%$). Regarding girls, a significant decrease in v was found when swimming with sensors ($p < 0.01$, $d = 0.39$; $\Delta = -1.99\%$). The SR (Panel B) and SL (Panel C) were not significantly different between free swim and sensors in all groups. Despite these, Δ in SR decreased by 1.63% and 2.42% with sensors overall and in the boys' group, respectively, while in the girls' group Δ in SR increased slightly ($\Delta = 0.93\%$). Overall, the SL decreased non-significantly ($\Delta = -0.09\%$), the boys' SL increased (Δ = 1.09%), and the girls' SL decreased (Δ = -1.13%). No differences ($p > 0.05$) were also found between sexes in *v*, SR, and SL.

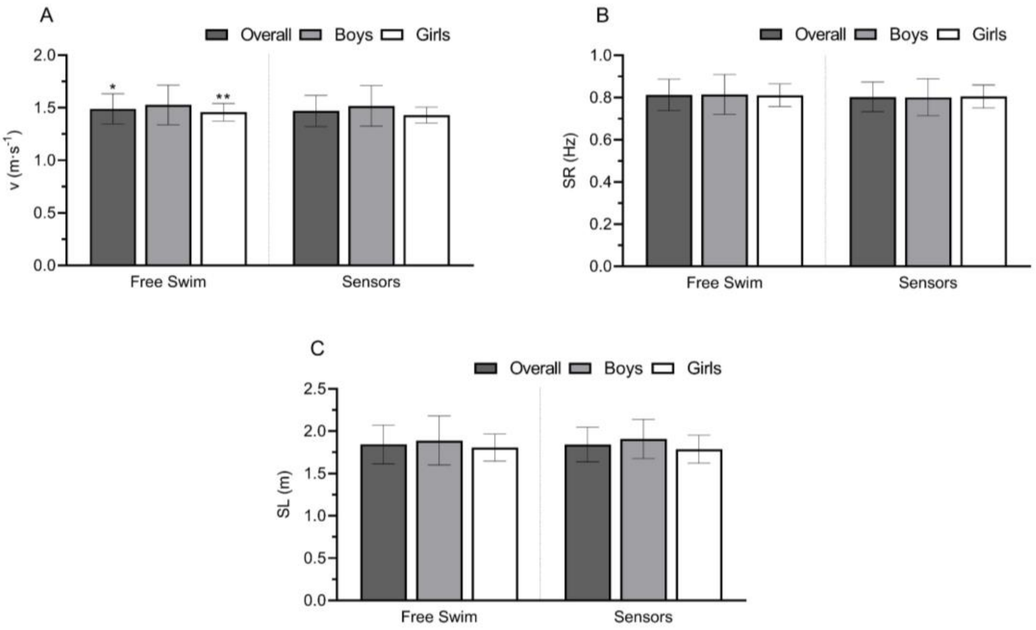

Figure 3. Comparison between free swim and sensors in stroke mechanics variables at front crawl. Panel A: swimming velocity (*v*); Panel B: stroke rate (SR); Panel C: stroke length (SL). *p ≤ 0.05 or **p ≤ 0.01, denotes a significant difference to sensors.

The swimming efficiency variables are shown in Figure 4. There was a significant decrease in the girls' SI (Panel A) with sensors ($p = 0.01$, $d = 0.20$; Δ = -3.15%). The Δ was -1.53% and 0.32% overall and in the boys' group, respectively. No differences were found in ηF ($p > 0.05$) for all groups. However, there was a slight tendency to decrease ηF when swimming with sensors (overall, Δ = -0.90%; boys, Δ = -0.79%; girls, Δ = -1.01%). The sex comparison revealed no differences ($p > 0.05$) in SI and ηF.

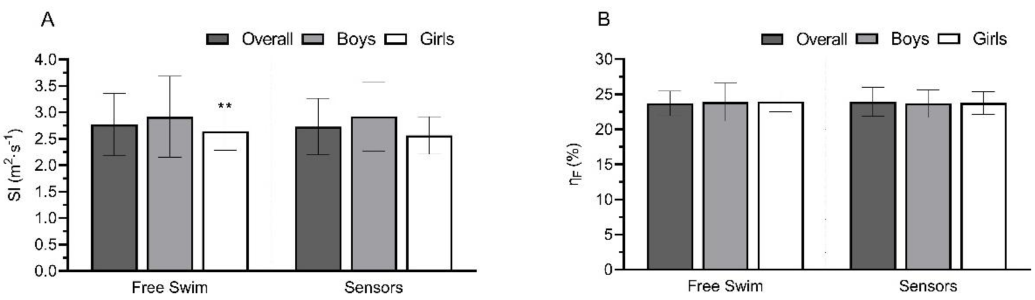

Figure 4. Comparison between free swim and sensors in swimming efficiency variables at front crawl. Panel A: stroke index (SI); Panel B: arm stroke efficiency (ηF). *p ≤ 0.05 or **p ≤ 0.01, denotes a significant difference to sensors.

Discussion

This study considered the technical constraints induced by the Aquanex System when swimming front crawl. The main finding was that swimming with sensors imposed trivial constraints on swimming performance and v but did not change the stroke mechanics or efficiency of young swimmers. Trivial constraints appeared to be more related to the girl's cohort. Nevertheless, there were no differences between sexes under both conditions for all variables.

Front crawl has been recognised as the fastest and most economical swimming stroke (Barbosa et al., 2010; Deschodt et al., 1999), being the most reported for field-oriented research purposes and for tracking swimming performance. Sprint events in short- and long-course swimming pools are characterised by generating a greater amount of propulsion in the water to reach higher velocity (Seifert et al., 2007). Thus, this kind of assessment is crucial and needs to be as accurate as possible, imposing the least constraints in the various aspects of the stroke.

Overall, front crawl swimming performance decreased significantly (1.30%) by adding the sensors (i.e., T25 increase), and thereby the v decreased as well by 1.42% during the T25. The v is highly dependent on the interaction between propulsive and resistive forces (Toussaint & Truijens, 2005). In front crawl, the upper limbs have been described as the most responsible for propulsion (Barbosa et al., 2020; Deschodt et al., 1999). As the system is carried by elastic straps in the upper limbs, swimmers might be under an additional drag. Likewise, changes in the palmar surface area due to the pressure sensors may also increase resistive forces (Santos et al., 2021). Previous studies using an additional device in the water (e.g., AquaTrainer® snorkel) have reported a similar decrease in swimming performance and v during front crawl and breaststroke (Barbosa et al., 2010; Conceição et al., 2013). The same authors argue that the decrease in v when adding the device, and therefore in the testing time, may be related to the existent passive and active drag.

Another important aspect is how the all-out effort was performed. Swimmers were assessed in a short distance (i.e., 25 m) with an in-water start. This was performed equally under both conditions without diving and adding a dolphin kick. When using sensors, it can be argued that the decrease found in swimming performance and v can be derived from a slower start as swimmers may need an initial adjustment to their swimming pattern. This may help explain the differences in the testing time (i.e., T25) between free swimming and swimming with sensors, but it does not impair the related mechanical aspects of the stroke.

The SF was assessed considering the 11th and the 24th m of the pool. It seems that swimmers were able to maintain their motion with and without the system. Theoretically, v can be modified by an increase or a decrease of the SR and SL (Barbosa et al., 2011). The results showed that the SF and the SL were not significantly different between both conditions in all groups, despite the differences previously found in v. Probably, the above-mentioned adaptation to the system (cable plus hand's set-up) after the start happens until the 11th m, not affecting both the SR and the SL measured afterwards. The same trend may be observed in efficiency. Since swimming efficiency was estimated based on stroke mechanics and/or anthropometric features, the SI and ηF were similar under both conditions for the pooled sample (i.e., overall group). Normally, the stroke mechanics variables, including the SR and the SL, and, therefore, the efficiency are dependent on limbs kinematics (Barbosa et al., 2010; Barbosa et al., 2011). Within this rationale, limbs trajectories and velocities may be decreased when using larger (Gourgoulis et al., 2006) and resistive (Guignard et al., 2017) devices. The system used in this study consisted of two small lightweight sensors attached to the swimmers' hands. Although it is considered an external device, it seems not to promote sufficient fatigue or increase resistive forces to change limb kinematics and stroke mechanics.

Boys and girls were analysed together at a first stage, since the sex gap is not an issue in this age group, at least with regard to pre-adolescence (Seifert et al., 2011; Zuniga et al., 2011). However, this does not mean that, at some point, the behaviour between boys and girls will not be interpreted separately (Barbosa et al., 2014). Within this approach, while girls showed decreases in v and SI when using the sensors, boys were not as constrained as girls. Explanations may rely on the boys' better ability for power output (Barbosa et al., 2015), which may enable them to adapt and sustain their effort even when using external devices. Although the sex comparison was performed, no differences were noted for all variables.

We may point out few limitations in the present research: (i) the v assessment was conducted based on T25 and distance (25 m), instead considering the range between the 11th and the 24th m used for the remaining variables; and (ii) the assessment of kinematics and timing should rely on cutting edge set-ups (e.g., high velocity cameras or phototiming) to get even a more precise measurement.

Conclusion

The Aquanex System seems not to induce constraints on the mechanics and efficiency of young swimmers, which can allow coaches to use it in their daily practice for monitoring of the training process. Despite that, coaches and researchers are advised to take some care in its application because during all-out efforts the initial velocity of the test can be compromised. As the cable can be an issue, a necessary quick adaptation to the device after the start is needed. As such, this can slightly compromise the mean velocity if we consider the overall distance covered for velocity estimation. Thus, measures such as swimming velocity, mechanics of the stroke, and efficiency, along with propulsive force should be retrieved further in the test for a more accurate assessment.

Chapter 4. Experimental studies: longitudinal approaches

Study 5. Within-season changes on young swimmers in-water force, performance, kinematics, and anthropometrics

Abstract

The aim of the present study was to analyze the within-season changes in young swimmers' in-water force, performance, kinematics, and anthropometrics. Twenty swimmers (11 girls and 14 boys) were assessed over a competitive season (four assessment moments). The in-water force of both hands (D, dominant; ND, non-dominant) was retrieved during two bouts of 25 m front crawl allowing the estimation of the symmetry index. The velocity (v25) was calculated from the time to complete the 25 m and considered as the performance outcome, while stroke rate, stroke length, and stroke index were used as kinematic parameters. Body mass, stature, arm span, and hand surface area were measured as anthropometric parameters. The in-water force (16-24%) and performance (8%) changed over the competitive season being more evident in the first months of the season. Plus, a higher asymmetric motion was found at the end of the season. For kinematics, only the stroke index changed between the beginning and the end of the season (12.7%). A time effect was also found in stature ($p<0.001$, $\eta_p^2 = 0.71$), arm span ($p<0.001$, $\eta_p^2 = 0.79$), and hand surface areas (D = $p < 0.001$, $\eta_p^2=0.63$; ND = $p < 0.001$, $\eta_p^2 = 0.666$.). The swimming performance was associated with in-water forces, stroke efficiency and anthropometric features in all moments of the season. Thus, in-water forces and performance improve over a full competitive season, accompanied by a natural anthropometric growth that may translate into a more efficient swimming pattern.

Key words: swimming, longitudinal, training periodization, biomechanics, sensors

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Introduction

Young swimmers' performance is characterized by a multifactorial and dynamic phenomenon, where anthropometrics and biomechanical characteristics (kinematics or hydrodynamics) define the energetic profile and may contribute to performance enhancement (Morais et al., 2021). For instance, parameters within the biomechanic domain seem to contribute approximately 50-60% to swimmers' performance (Morais et al., 2012). Research on young swimmers has been largely focused on such parameters, but most previous studies presented a cross-sectional research design. Such interventions are less comprehensive and informative than longitudinal designs about the cause-and-effect relationships from a long-term perspective (Costa, Bragada, Marinho et al., 2012). So, monitoring long-term changes in swimming can be a useful approach to understand training effects within a competitive season.

Swimmers typically undergo an annual traditional training periodization with two or three peak performance forms (i.e., macrocycles). Since they go through a growth and biological maturation process, training programs focus mainly on the acquisition of fundamental motor skills (Lang & Light, 2010; Martindale et al., 2005). Growth spurts usually occur within a competitive season (Abbott et al., 2021), and are accompanied by changes in other performance-related parameters. To date, the few available longitudinal studies in young swimmers were mainly directed towards assessing anthropometric (Fiori et al., 2022), energetic (Zacca et al., 2020), kinematic (Morais et al., 2013), efficiency (Morais et al., 2017) or dry-land strength/power (Batalha et al., 2013; Garrido et al., 2010). Young swimmers are prone to improve kinematics along with an increase in anthropometric traits (Morais et al., 2013; Lätt et al., 2009a, 2009b). Improvements in energetics (oxygen uptake) and efficiency (stroke index, SI) also allowed a performance enhancement, mainly in middle-distance events (Ferreira et al., 2021; Zacca et al., 2020). Although changes have been observed between the beginning and the end of the season, some impairments in stroke mechanics can occur at specific moments (Morais et al., 2013). Hence, performance levels should be seen as dynamic, and any shift within a season may be dependent on the training program, swimmers' sex, growth, or maturational status.

Deterministic models pointed out the influence of anthropometrics and kinetics on swimming kinematics (Barbosa et al., 2013). It means that swimming velocity depends on the interaction of propulsive and drag forces being the in-water force influenced by the swimmer's technique and strength levels. So, in-water force production may determine the overall stroke mechanics and then influence the performance, especially in sprint events (Gatta et al., 2016). Long-term studies on in-water force changes only complied dry-land training, tapering, and warm-up effects ranging between 1 and 10 weeks (Santos et al., 2021). To date, no study was found aiming to follow-up in-water forces of younger swimmers and their (non) linear fluctuations during a full competitive season. As the ability to apply force in the water could be a key factor to swimmers' forward displacement, a deeper understanding of how in-water force progresses at different moments over a so long time is welcome. The present study aimed to analyze the effect of a competitive season on the in-water force, performance, kinematics, and anthropometrics of young swimmers. It was hypothesized that performance and kinematics would change over the competitive season due to the enhancement of in-water forces accompanied by the natural growth of the swimmers.

Materials and Methods

Participants

Twenty-five highly trained (Mckay et al., 2022) swimmers (11 girls and 14 boys: 12.04±0.16) were recruited from a local swimming squad. The inclusion criteria for the participants were: (i) having a minimum of two years in competitive swimming in regional or national events; (ii) practising more than four swim training sessions per week; (iii) attending all data collection moments; and (iv) having suffered any injuries in the past six months after the beginning and during the competitive season. Swimmers who did not meet these criteria from the beginning of the season until the data collection were not considered. The swimmers' parents or guardians were informed about the benefits and experimental risks before signing a written informed consent form. All procedures were in accordance with the Declaration of Helsinki and approved by the Institutional Ethics Committee of the University of Beira Interior (code: CE-UBI-Pj-2020-058).

Study design

A longitudinal follow-up design was selected over one competitive season. Swimmers were evaluated during a traditional training periodization with three peak forms. The evaluation moments (M_i) were conducted before the beginning of the season (M_1) and after the main competition at the first (M_2), second (M_3), and third (M_4) macrocycle. The distribution of training volume (km/week^{-1}) and training intensity (%) of the three macrocycles are shown in Figure 1. The in-water experimental testing was carried out in a 25 m indoor swimming pool with a mean water temperature of 27.5°C. After a standardized warm-up (400 m swim, 100 m pull, 100 kick, 4x50 m at increasing speed, 200 m easy swim) performed individually (Morouço et al., 2018), swimmers were instructed to perform two maximum bouts of 25 m front crawl (full-body; 2 x 25 m) with their normal breathing pattern for biomechanical and performance measurements. The test began with an in-water push-off without gliding controlled by an auditory signal. All swimmers were asked to abstain from intense exercise and tests were conducted at the same time of the day to avoid systematic bias due to fatigue and circadian variation.

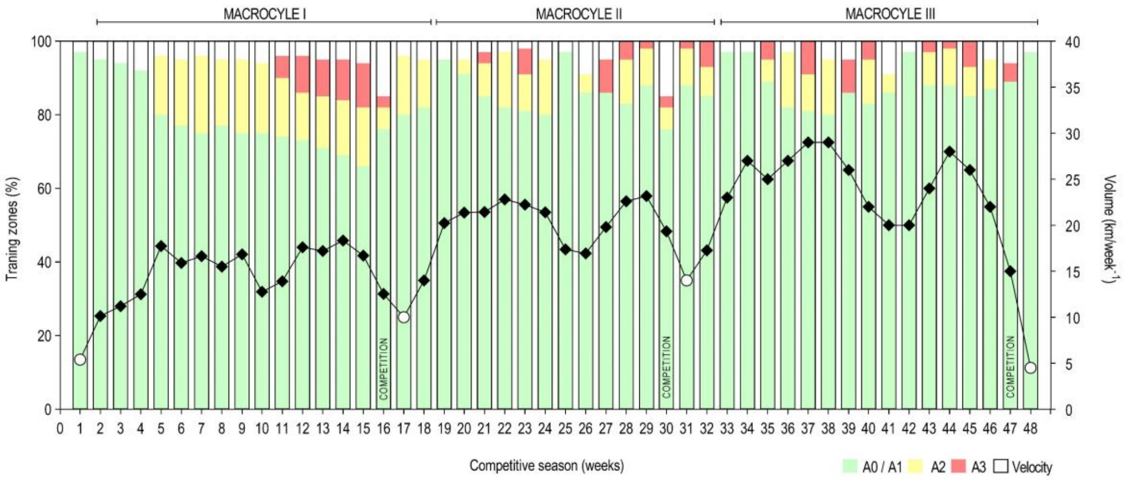

Figure 1. The distribution of training volume (km/week-1) and training intensity (%) over the competitive season (three macrocycles). White dots represent the four assessment moments.

Anthropometrics and biological maturation

All measurements were carried out with swimmers wearing a regular textile swimsuit and a cap. A single observer measured body mass, stature, sitting height, arm length and arm span following recommended and standardized protocols (Lohman et al., 1988). Stature, sitting height, and arm span were measured to the nearest 0.1 cm using a portable stadiometer (SECA, 242, Hamburg, Germany) and flexible tape (RossCraft, Canada). Estimated leg length was calculated as the difference between stature and sitting height. Body mass was measured to the nearest 0.1 kg using a portable scale (TANITA, BC-730, Amsterdam, Netherlands). Body mass index was calculated from the body mass and the height (in kg/m^2). The hand surface area (HSA, in cm^2) for the dominant and non-dominant sides was measured by digital photogrammetry (Moreira et al., 2014). Swimmers placed each hand on a flat surface with a 2D calibration frame (3x3 cm) and from there all images were exported to an on-screen digitizer (Universal Desktop Ruler, v3.8, AVPSoft, USA). The swimmers' hand dominance was obtained by self-report. Before the M_1, the maturity offset (MO) was obtained from a gender-specific algorithm based on the swimmers' demographics (Mirwarld et al., 2002). Swimmers' MO was interpreted at the beginning of the season as if MO < – 0.5 years, pre-PHV; if – 0.50 > MO ≤ 0.50 years, mid-PHV; and if MO > 0.50 years, post-PHV.

Biomechanical and performance parameters

In-water kinetics was measured using a differential pressure system composed of two hand sensors (Type A, Swimming Technology Research, Richmond, VA, USA). The Aquanex system has been proposed as a reliable method to measure pressure differences between the palmar and dorsal surfaces of both hands (Santos et al., 2022a) without imposing any constraints on the mechanics or efficiency of young swimmers (Santos et al., 2022b). Sensors were attached by a cable to a two-channel A/D converter connected to a laptop with the Aquanex software (v.4.1, Model DU2, Swimming Technology Research, Richmond, VA, USA). The system was carried with elastic straps on swimmers' shoulders and arms. The calibration was done as reported elsewhere (Santos et al., 2022a) and data were acquired with a sampling frequency of 100 Hz.

Hand resultant force (in N) was derived from the product of differential pressures by the HSA of each swimmer. Force-time curves of underwater paths retrieved in all M_i were analysed between the 11th and 24th m. The mean peak force (F_{PEAK}, in N) of the dominant and non-dominant hand was defined as the mean of the maximum values (i.e., peak) obtained in all stroke cycles of the defined interval. The subsequent peak force (SF_{PEAK}, in N) was defined as the maximum value (i.e., peak) obtained in each two subsequent force-time curves. All SF_{PEAK} were retrieved when the first upper-limb (dominant or non-dominant) reached the 11th, and then the subsequent one (opposite) was also considered. Two visual marks were applied in the defined interval and the distance covered by the swimmers was recorded using two video cameras (Sony, HDR-CX 240, Japan) at a sampling frequency of 50 Hz (Figure 2). Force data were imported into a signal-processing software (AcqKnowledge v.3.7.3, Biopac Systems, Santa Barbara, CA, USA) and the signal was handled with a 5 Hz cut-off low-pass fourth-order Butterworth filter. Therefore, the Symmetry Index (SyI, in %) was estimated using the SF_{PEAK} data of both hands (Robinson et al., 1987). Data were interpreted as; if SyI = 0%, perfect symmetry; if 0% > SyI < 10%, symmetric motion; and if SyI ≥ 10%, asymmetric motion.

In-water kinematic and temporal parameters were retrieved during the 2 x 25 m front-crawl swimming. Swimming performance was manually assessed by a certified coach using a stopwatch (FINIS 3x100, Finis Inc., USA) and considered as the time spent (in s) to cover 25 m (T25). The swimming velocity (v25, in $m \cdot s^{-1}$) was calculated based on the ratio between the distance of 25 m and the T25. The stroke rate (SR, in Hz) was assessed with a chrono-frequency meter (FINIS 3x300, Finis Inc., USA) from three consecutive stroke cycles between the 11th and the 24th m (Figure 2), and the stroke length (SL, in m) was estimated (SL = v / SR) as reported elsewhere (Craig & Pendergast, 1979). The stroke index (SI, in $m^2 \cdot s^{-1}$) was computed (SI = v · SL) (Costill et al., 1985).

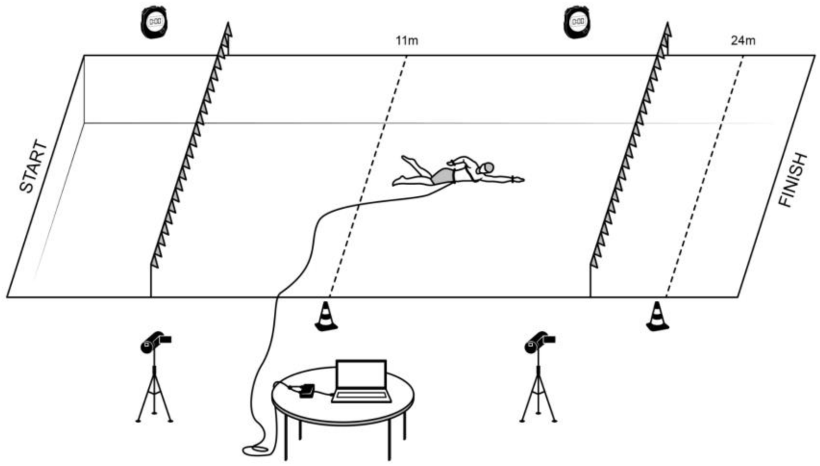

Figure 2. In-water setup for biomechanical and performance assessments.

Statistical analysis

The Shapiro-Wilk test was used to assess the normality of data. A log transformation (Log10) was performed if the assumption of normality was violated. Data were back-transformed from the log scale for presentation in the results. The mean and one standard deviation (M±1SD) were computed as descriptive statistics. An unpaired t-test was used in each variable to compare differences between girls and boys. Repeated measures ANOVA followed by the Bonferroni *post-hoc* test was performed to analyse the variation between the M_i. The assumptions of an ANOVA were tested, and Greenhouse-Geisser correction was considered if the assumption of sphericity was violated. Partial Eta Squared (η_p^2) was considered as an effect size measure and interpreted as reported elsewhere (Ferguson, 2009): no effect if $0 < \eta_p^2 \leq 0.04$; a minimum effect if $0.04 > \eta_p^2 \leq 0.25$; a moderate effect if $0.25 > \eta_p^2 \leq 0.64$; and a strong effect if $\eta_p^2 > 0.64$. The percentage of variation (Δ) between M_i was calculated (e.g., $[M_1 - M_2] / [M_1] \cdot 100$). The associations between performance (v25) and the remained parameters at the same M_i were also analyzed with the Pearson Correlation Coefficient (r) being interpreted as high if $r \geq 0.60$, moderate if $0.30 \geq r < 0.60$, and low if $r < 0.30$ (Malina, 2001). All statistical analyses were performed using the SPSS software (v.27, IBM, SPSS Inc., Chicago, IL, USA) and GraphPad Prism (v.9, GraphPad Software, San Diego, CA, USA). The statistical significance was set at $p \leq 0.05$.

Results

Boys and girls differed in statute (M_4) and arm span (M_4) but not in the remaining variables. As such, girls and boys were pooled and analysed together. The swimmer's MO was categorized as pre- and mid-PHV (−1.13±0.74) at M_1. The effects of the competitive season on the in-water force, symmetry, performance, kinematics and anthropometrics of young swimmers are presented in Table 1. A minimum time effect was found in all variables except for anthropometrics, where the stature, arm span, HSA D and ND changed throughout the various M_i with a moderate-strong effect.

Table 1. Effects of the full competitive season on in-water force, performance, kinematic and anthropometric variables of young swimmers.

Variables	Time effect			Moments (M±1SD)			
	F	p	η_p^2	M_1	M_2	M_3	M_4
In-water force							
F_{PEAK} D, N	3.956	0.019	0.14	45.96±10.48	50.82±12.31	48.77±13.88	53.41±17.23
F_{PEAK} ND, N	7.206	<0.001	0.23	45.23±11.28	51.37±13.53	53.97±17.23	55.50±18.85
SF_{PEAK} D, N	3.332	0.024	0.12	46.48±13.49	52.46±14.48	52.91±16.98	55.58±19.11
SF_{PEAK} ND, N	3.946	0.012	0.14	47.74±11.67	55.74±14.51	55.26±17.81	57.51±23.62
SyI, %	3.810	0.014	0.14	17.13±12.42	19.03±14.74	16.38±15.39	28.42±17.92
Performance and kinematics							
T25, s	13.739	<0.001	0.36	17.72±1.71	16.89±1.40	17.04±1.59	16.50±1.50
v25, $m \cdot s^{-1}$	13.489	<0.001	0.36	1.42±0.14	1.49±0.12	1.48±0.14	1.53±0.14
SR, Hz	1.186	0.321	0.05	0.79±0.10	0.81±0.06	0.82±0.08	0.82±0.08
SL, m	0.998	0.399	0.04	1.81±0.21	1.85±0.17	1.82±0.15	1.86±0.12
SI, $m^2 \cdot s^{-1}$	6.665	<0.001	0.22	2.57±0.44	2.78±0.43	2.70±0.40	2.85±0.36
Anthropometrics							
Body mass, kg	2.917	0.087	0.11	48.13±8.63	48.12±7.49	49.11±7.73	49.37±7.55
Stature, cm	58.672	<0.001	0.71	156.59±8.07	157.80±8.05	158.74±8.22	160.17±8.31
BMI, kg/m^{-2}	1.340	0.268	0.05	19.57±2.96	19.26±2.25	19.43±2.25	19.18±2.10
Arm span, cm	87.967	<0.001	0.79	156.71±9.84	157.98±9.98	160.50±10.32	162.32±10.62
HSA D, cm^2	40.801	<0.001	0.63	101.36±12.09	105.72±13.02	109.03±14.31	112.08±16.60
HSA ND, cm^2	47.210	<0.001	0.66	101.46±13.48	106.39±14.23	109.50±14.94	112.17±16.16

D, dominant; ND, non-dominant; M_i, moments; F_{PEAK}, mean peak force; SF_{PEAK}, subsequent peak force; SyI, symmetry index; T25, time; v25, swimming velocity; SR, stroke rate; SL, stroke length, SI, stroke index; BMI, body mass index; HSA, hand surface area.

Repeated measures between the M_i and the variation (Δ) are shown in Figures 3-5.

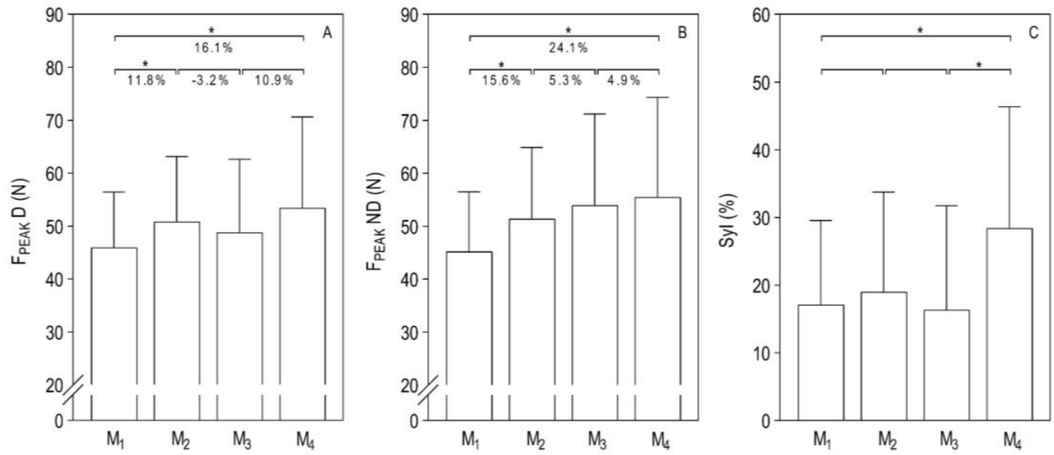

Figure 3. Effects of competitive season on swimmers' in-water force and symmetry. Panel A and B, mean peak forces for dominant (F_{PEAK} D) and non-dominant (F_{PEAK} ND) limbs; Panel C, symmetry index (SyI). *, p ≤ 0.05; **, p ≤ 0.01

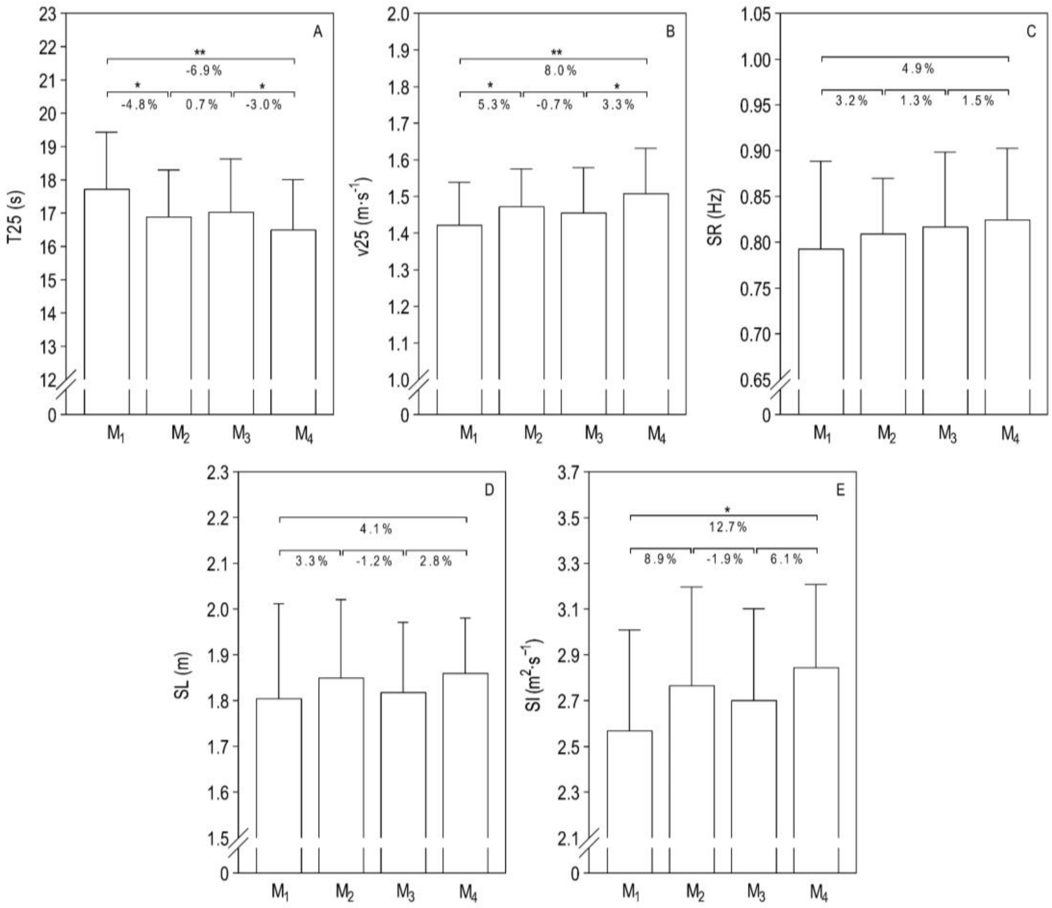

Figure 4. Effects of competitive season on swimmers' performance and kinematics. Panel A, time of 25 m (T25); Panel B, velocity of 25 m (v25); Panel C, stroke rate (SR); Panel D, stroke length (SL); Panel E, stroke index (SI). *, p ≤ 0.05; **, p ≤ 0.01

The Pearson Correlation Coefficients between performance and the remained variables are shown in Table 3. Moderate to high associations were found with F_{PEAK} D, F_{PEAK} ND, SI, stature, arm span, HSA D and HSA ND throughout the competitive season. The performance was moderately associated with SR in M_1 and highly associated with M_3 and M_4. Regarding SL, a high association was found in M_2. The BM showed a moderate association in M_3 and M_4.

Discussion

The aim of this study was to analyze young swimmers' in-water force, performance, kinematics, and anthropometrics throughout a competitive season. The main finding was that in-water force and performance changed over the competitive season. Despite the natural anthropometrical growth, only the stroke index changed between the beginning and the end of the season, translating into a more efficient swimming pattern. The swimming performance is associated with in-water forces, stroke efficiency or anthropometric features when different moments of the season are considered.

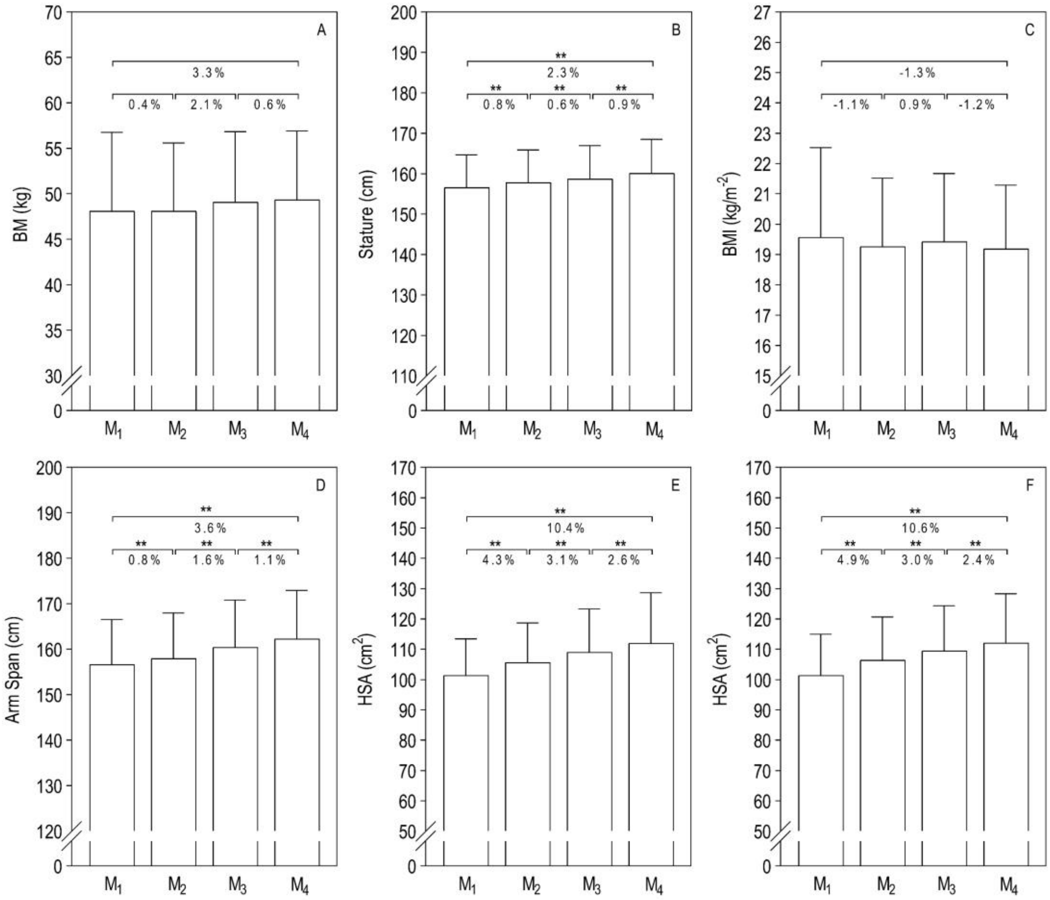

Figure 5. Effects of competitive season on swimmers' anthropometrics. BMI, body mass index; D, dominant; ND, non-dominant; HSA, hand surface area. *, $p \leq 0.05$; **, $p \leq 0.01$

Table 3. Associations between the performance (v25) and the in-water force, kinematic and anthropometric variables according to each M_i.

Variables	v25			
	M1	M2	M3	M4
FPEAK D, N	0.655**	0.507**	0.492*	0.458*
FPEAK ND, N	0.677**	0.707**	0.705**	0.577**
SyI, %	0.395	-0.115	-0.153	-0.203
SR, Hz	0.540**	0.309	0.606**	0.727**
SL, m	0.316	0.639**	0.376	0.300
SI, $m^2 \cdot s^{-1}$	0.766**	0.895**	0.850**	0.863**
BM, kg	0.291	0.318	0.433*	0.401*
Stature, cm	0.585**	0.537**	0.524**	0.625**
Arm Span, cm	0.541**	0.537**	0.565**	0.642**
HSA D, cm^2	0.482*	0.667**	0.661**	0.691**
HSA ND, cm^2	0.508**	0.705**	0.697**	0.736**

v25, swimming velocity; M_i, moments; FPEAK, mean peak force; D, dominant; ND, non-dominant; SyI, symmetry index; SR, stroke rate; SL, stroke length; SI, stroke index; BM, body mass; HSA, hand surface area

Young swimmers are able to increase in-water forces (16-24% Δ) over a competitive season being more evident in the first months of the season. At early ages, the training should focus on technique, but a given distance should be covered in the shortest time possible (Morais et al., 2021). So, an enhancement in swimming performance is underpinned by an increase in the water force production while diminishing drag (Barbosa et al., 2013). Few studies highlighted the long-term effects on swimmers in-water forces (Santos et al., 2021) being mainly related to the effects of using propulsion devices (Barbosa et al., 2020), warm-up routines (Neiva et al., 2011) or detraining (Ruiz-Navarro et al., 2022; Neufer et al., 1987; Santos et al., 2023). For instance, a six-week training cessation seems not to reduce the in-water force of young competitive swimmers (Santos et al., 2023). However, to date, no study was conducted to understand the force behaviour throughout a full competitive season. Deterministic models point out that in-water forces could be determined by muscular strength levels (Barbosa et al., 2013). At least for young swimmers, the swimming training promotes a progressive increase in strength shoulder rotators over a competitive season (Batalha et al., 2013). So, it can be argued that a similar trend seems to occur for dry-land strength and in-water forces. Although dry-land strength gains showed a null transfer to water force production in prepubescent swimmers (Amaro et al., 2017), further studies are required to understand if, at any moment of the season, this transfer could happen.

Another cue arises in the limb's dominance, as a higher proportion to increase force over the season seems to happen in the non-dominant side. In fact, choosing to breathe unilaterally (the most frequent breathing pattern) can trigger the application of a higher force on the contralateral side (Tourny-Chollet et al., 2009). At least in dry-land, an increase in muscular imbalances in young swimmers has been reported for internal and external shoulder rotators after a full competitive season (Batalha et al., 2013). The same trend seems to occur with the in-water forces, as a higher contralateral asymmetric motion (i.e., higher SyI) was found at the end of the season. Still, the degree of imbalance may dissipate over the detraining period where the SyI may decrease after the summer break (–46.7% Δ; Santos et al., 2023). So, it can be stated that a competitive season can lead to a more asymmetric force pattern with each stroke cycle. Thus, future research should try to understand the effect of breathing and dry-land strength on in-water forces, establishing a cause-effect relationship throughout a competitive season.

The main performance improvements (improved by 8.0 over the season) occurred in the first (5.3%) and third (3.3%) macrocycles, while SI changes were only observed between the beginning and the end of the season (12.7%). Previous literature displayed similar improvements in 100 m (Morais et al., 2013), 200 m (Fiori et al., 2022a) and 400 m front-crawl (Ferreira et al., 2020; Lätt et al., 2009a, 2009b; Zacca et al., 2020) throughout a competitive season. Increases in velocity can be reached using different individual SR-SL relationships in both adults and young swimmers (Barbosa et al., 2008;

Barbosa et al., 2010). However, improving SR while maintaining SL is a challenge at such early ages (Moreira et al., 2014). The present follow-up showed that young swimmers tended to improve SR and SL in the most moments, but without statistical meaning. Morais et al. (2013) and Lätt et al. (2009b) also noticed no differences in SR between the beginning and the end of the season for girls and boys. Plus, national and international swimmers also showed the same trend for SR and SL (Costa, Bragada, Meijas et al., 2012); however, when maximum technical skill is reached, changes in stroke mechanics are trivial. Meanwhile, changes in motor control due to the growth may influence stroke mechanics and efficiency in young swimmers (Seifert el al., 2004) and some kind of "relearning" of stroke mechanics should be considered whenever growth spurts occur.

The second macrocycle (M_2-M_3) showed a non-linear change (Figure 2) and is worthy of particular awareness. The performance (-0.7%), F_{PEAK} D (-3.2%), SL (-1.2%) and SI (-1.9%) were reduced at this specific moment. A similar impairment in performance (i.e., velocity) was found in T100 front-crawl (Morais et al., 2013). Here, the training periodization could impact performance and technical parameters in a given time. The performance was high associated with SL only M_2 (end of the first macrocycle), while the remained M_i demonstrated a moderate to high association with SR. At some moment during the annual training, young swimmers might be not completely effective in getting technical adaptations while working for difference distances (Strzala & Tyka, 2007). Despite that, some increases in SR, associated with a slight decrease in SL, should not be considered ineffective (Huot-Marchand et al., 2005). However, at so younger ages, the technical adjustment in individual SR-SL relationships seems difficult to acquire to maintain optimal speed and efficiency (Strzala & Tyka, 2007). One might consider that swimmers of the present study were under the same phenomenon since the SI showed a non-linear change. However, as SI is based on an estimation from kinematic parameters, changes should occur in a manner way. Still, should point out that young swimmers are more efficient after a training season probably due to an improvement in technique and anthropometric traits.

After 48 weeks, young swimmers were taller (3.6 cm) with a longer arm span (5.6 cm) and hand surface area (D: 10.7 cm^2; ND: 10.7 cm^2). Such parameters also showed a high association with performance. Variations during circumpubertal years (–2 to +2 years of PHV) are fundamentally linked to growth maturation (Malina et al., 2004). So, previous studies conducted with young swimmers also reported changes throughout a macrocycle (Ferreira et al., 2019), a full competitive season (Fiori et al., 2022a; Lätt et al., 2009a, 2009b; Morais et al., 2013), and a detraining period (Fiori et al., 2022b; Santos et al., 2023).

Some limitations can be acknowledged in the present study and improved: (i) the biological maturation was assessed by an indirect method to characterize swimmers in M_1. So, future studies are required to deeply understand the role of long-term changes in in-water forces and the effect of biological maturation in the same competitive age group. (ii) split the data according to the swimmers' gender (i.e., maturity offset treatment in cohorts of girls and boys) can also be beneficial for tracking swimmers' features; and (iii) the effect of in-water forces and their relationship with performance and dry-land strength in other swimming strokes and distances could also provide a deeper insight into the topic.

Conclusion

The in-water forces and performance improve over a full competitive season, accompanied by a natural anthropometric growth that may translate into a more efficient swimming pattern. It should be expected that swimming performance would be associated with in-water forces, stroke efficiency or anthropometric features when different moments of the season are considered. So, coaches should be aware that, at a given moment of the season, young swimmers may not be able to apply effectively in-water force and shift their technique to desired levels leading to an efficiency loss.

Study 6. The effects of six-week training cessation on anthropometrics, in-water force, performance, and kinematics of young competitive swimmers: a maturity development approach

Abstract

The aim of the present study was to examine the effects of six weeks of training cessation on young swimmers' anthropometrics, in-water force, performance, and kinematics according to biological maturation. Eighteen swimmers (7 girls: 12.43±0.73 years; 11 boys: 13.27±0.79 years) were assessed pre- and post-test six weeks apart. Body mass, stature, arm span, and hand surface area were measured as anthropometric parameters, while biological maturation was estimated. The in-water force was retrieved during two bouts of 25 m front crawl allowing the estimation of the symmetry index. The time to complete the 25 m was considered the performance outcome, while velocity, stroke rate, stroke length, stroke index, and arm stroke efficiency were used as kinematic parameters. All anthropometric parameters increased during the detraining period. Although the in-water force remained unchanged, the magnitude of the effects was large for the symmetry index ($p = 0.021$; $d = 0.87$). For the pooled sample, neither performance nor kinematics changed after detraining, but the stroke index increased ($p = 0.054$; $d = 0.27$). Pre-PHV swimmers showed unchanged values in all parameters, despite natural growth. Mid-PHV swimmers showed a similar trend, in addition to reductions in stroke rate ($P = 0.040$; $d = 0.60$) and increases in stroke length ($p = 0.043$; $d = 1.00$). In-water force, performance, and kinematics were not impaired after six weeks of detraining in a group of young swimmers. Given intra-individual differences according to maturity status, coaches should be aware that distinct trends within the group can be found.

Key words: detraining, swimming, biomechanics, biological maturation, growth

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Introduction

A typical competitive season is preceded by a training cessation (off-season) that may differ in duration due to the swimmer's competitive level and chronological age. Training cessation is characterized by a temporary break from systematic training programs (Mujika & Padilla, 2000). As swimming depends on a multifactorial process (Barbosa et al., 2010), a deeper understanding of how the cessation of training can promote fluctuations in different aspects of performance is necessary. While cessation of swimming training has been shown to impair some performance-related parameters in mature swimmers (Arsoniadis et al., 2022; Ruiz-Navarro et al., 2022), some mixed findings appear to exist in younger swimmers (Fiori et al., 2022; Morais et al., 2022; Moreira et al., 2014; Zacca et al., 2019).

Young swimmers typically have an off-season period between 4 and 11 weeks (Morais et al., 2022; Zacca et al., 2019). Despite the absence of systematic and oriented training during this break, previous studies with young swimmers have shown improvements in performance or kinematics (Moreira et al., 2014) and maintenance of dry-land strength (Garrido et al., 2010). A weakening in performance (Morais et al., 2022) or a decrease in energy capacity has also been found (Zacca et al., 2019). However, data on the effects of detraining on swimming kinetics are still lacking. The few studies found in the literature on this subject focus on male adult swimmers and show lower values of in-water forces after the cessation of training (Neufer et al., 1987; Ruiz-Navarro et al., 2022) The swimmer's capacity to move forward depends on the ability to effectively apply force in the water and on drag forces acting in the opposite direction of the swimmer's displacement (Santos et al., 2021). So, evidence is necessary concerning the effects of training cessation on the ability to apply forces in the water, particularly at early competitive ages.

Competition among young swimmers relies on chronological age and gender. Those are competitors that undergo growth and biological maturation leading to (non) linear fluctuations of performance-related parameters (Morais et al., 2021). Within the normal range, peak height velocity (PHV) usually occurs around the age of 13-15 for boys and two years earlier for girls (Malina et al., 2004). Although girls and boys are usually grouped together in most of the research (Barbosa et al., 2015), some distinct maturation rates may translate into some degree of heterogeneity within the same competitive age group. Few studies have analyzed the effects of growth according to the sex of the swimmers (Morais et al., 2022), but they have not adequately examined the effects of detraining considering the circumpubertal years. Improvements in performance after 10 weeks of training cessation were associated with normal growth (i.e., changes in the anthropometric profile) in pre-pubertal swimmers (Moreira et al., 2014), regardless of maturity. Thus, the use of maturity offset is justified to better understand the effects of training cessation on the kinetic characteristics of young swimmers. This will help coaches properly define the traditional training periodization, particularly the first peak performance form (i.e., macrocycle) of the upcoming competitive season.

The aim of the present study was twofold: (i) to analyze the effect of six weeks of training cessation on anthropometrics, in-water force, performance, and kinematics of young swimmers; and (ii) to determine whether changes in such parameters rely on the biological maturation of young swimmers. It was hypothesized that training cessation would not impair the performance, in-water force, and kinematics due to swimmers' natural growth (i.e., changes in the anthropometrics).

Materials and Methods

Participants

Eighteen highly trained (McKay et al., 2022) swimmers (7 girls: 12.43±0.73 years; 11 boys: 13.27±0.79 years) were recruited from a local swimming squad. The inclusion criteria of the participants were: (i) having a minimum of two years of competitive swimming in regional or national events; (ii) practicing more than four swimming training sessions per week; (iii) not being a post-pubertal swimmer; (iv) not having suffered any injury in the last six months (pre-test) and in the off-season (post-test); and (v) being previously familiar with the hand differential pressure system. Swimmers who did not meet these criteria from the beginning of the season until data collection were not considered. The swimmers' parents or guardians were informed about the benefits and experimental risks before signing a written informed consent form. All procedures were in accordance with the Declaration of Helsinki and approved by the Institutional Ethics Committee of the University of Beira Interior (code: CE-UBI-Pj-2020-058).

Design

A longitudinal design with two different time points (pre- and post-test) six weeks apart was selected. The pre-test was conducted at the end of the competitive season (i.e., competitive peak form) and the post-test during the first week of the following competitive season. The mean training volume and intensity per week during the last macrocycle of the season and after the six-week training cessation are shown in Figure 1. The in-water experimental testing was carried out in a 25 m indoor swimming pool (water temperature: 27.5°C) during two days. Swimmers were instructed to refrain from intense exercise and tests were performed at the same time of the day to avoid systematic bias due to fatigue and circadian variation.

Data collection

Anthropometrics

Swimmers wore a regular textile swimsuit and cap during all measurements. Following the recommended and standardized protocols (Lohman et al., 1988), body mass, stature, sitting height, arm length and arm span were measured by a single person. Stature, sitting height, arm length and arm span were measured to the nearest 0.1 cm using a portable stadiometer (SECA, 242, Hamburg, Germany) and a flexible tape (RossCraft, Canada). Estimated leg length was calculated as the difference between stature and sitting height. Body mass was measured to the nearest 0.1 kg using a portable scale (TANITA, BC-730, Amsterdam, Netherlands). Body mass index was calculated from the body mass and the height (in kg/m^2). The hand surface area (HSA, in cm^2) for the dominant and non-dominant sides was measured by digital photogrammetry (Moreira et al., 2014). Swimmers placed each hand on a flat surface with a 2D calibration frame (3x3 cm), and from there all images were exported to an on-screen digitizer that allows for precise measurement of areas (Universal Desktop Ruler, v3.8, AVPSoft, USA). Swimmers' hand dominance was obtained by self-report.

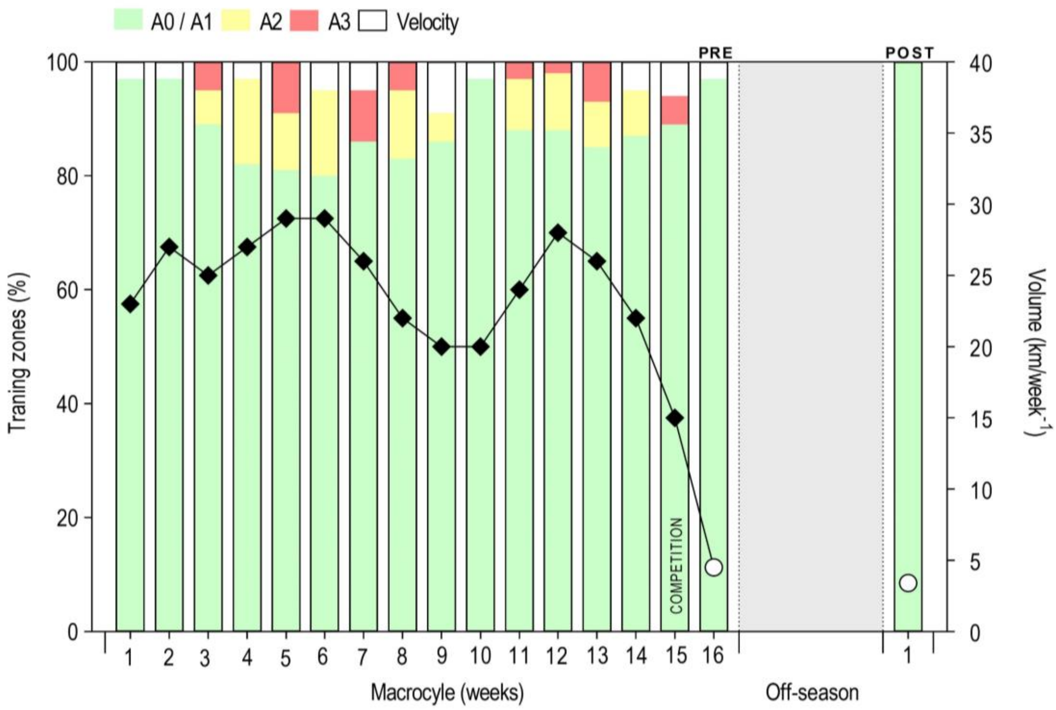

Figure 1. Training intensity and volume per week of the macrocycle before the training cessation. Pre, pre-test; Post, post-test.

Chronological age and biological maturation

The chronological age (CA) was calculated to the nearest 0.1 year. A non-invasive biological maturation approach was used to estimate peak height velocity (PHV). Maturity offset (MO) was obtained from a gender-specific algorithm based on the swimmers' demographics (i.e., CA, body mass, stature, sitting stature, and estimated leg length) as described by Mirwarld et al. (2002) and presented in Equations 1 and 2. A negative MO (i.e., MO < 0 years) indicates the time (in years) to reach the age peak height, while a positive MO (i.e., MO ≥ 0 years) indicates whether it was reached or exceeded. For further analysis, swimmers were categorized according to the stage of MO: pre-PHV, if < −0.50 years; and mid-PHV, if > −0.50 to 0.50 years.

(1) MO girls (years): −9.376 + (0.0001882 · [leg length · sitting height]) + (−0.0022 · [CA · leg length]) + (0.005841 · [CA · sitting height]) − (0.002658 · [CA · body mass]) + (0.07693 · ([body mass / stature] · 100))

(2) MO boys (years): −9.236 + (0.0002708 · [leg length · sitting height]) + (−0.001663 · [CA · leg length]) + (0.007216 · [CA · sitting height]) + (0.02292 · ([body mass/ stature] · 100))

In-water force

A standardized warm-up (400 m swim, 100 m pull, 100 kick, 4x50 m at increasing speed, 200 m easy swim) was performed individually (Morouço et al., 2018) before the in-water data collection pre- and post-test. Then, the swimmers were instructed to perform two maximum bouts of 25 m front crawl (full-body) with their normal breathing pattern for sprint events. The test started with an in-water push-off without gliding controlled by an auditory signal. A reliable and user-friendly differential pressure system (Santos et al., 2022a; 2022b) consisting of two hand sensors (Type A, Swimming Technology Research, Richmond, VA, USA) was used to measure pressure differences between the palmar and dorsal surfaces of both hands. The resultant hand force (in N) was derived from the product of the differential pressures and the HSA of each swimmer (i.e., differential pressure · hand surface area; Santos et al., 2022b). Sensors were attached by a cable to a two-channel A/D converter connected to a laptop with the Aquanex software (v.4.1, Model DU2, Swimming Technology Research, Richmond, VA, USA). The system calibration was performed as reported elsewhere19 and the data was acquired with a sampling frequency of 100 Hz.

Force-time curves of underwater paths retrieved in pre- and post-tests were analyzed between the 11th and 24th m. The mean peak force (F_{PEAK}, in N) of the dominant and non-dominant upper limbs was defined as the mean of the maximum values (i.e., peak) obtained in all stroke cycles of the defined interval (i.e., 13 m). The subsequent peak force (SF_{PEAK}, in N) was defined as the maximum value (i.e., peak) obtained in each two subsequent force-time curves. All SF_{PEAK} were retrieved when the first upper-limb (dominant or non-dominant) reached the 11th, and then the subsequent one (opposite) was also considered. Two visual marks were applied in the defined interval and the distance covered by the swimmers was recorded using two video cameras (Sony, HDR-CX 240, Japan) at a sampling frequency of 50 Hz. Force data were imported into a signal-processing software (AcqKnowledge v.3.7.3, Biopac Systems, Santa Barbara, CA, USA) and the signal was handled with a 5 Hz cut-off low-pass fourth order Butterworth filter. Only the best maximum bout was considered for further analysis. The Symmetry Index (SyI, in %) was estimated using the SF_{PEAK} data and as proposed elsewhere (Robinson et al., 1987). Data were interpreted as; if SyI = 0%, perfect symmetry; if 0% > SyI < 10%, symmetric motion; and if SyI ≥ 10%, asymmetric motion.

Performance and kinematic parameters

Temporal and kinematic parameters were retrieved during a 2 x 25 m front-crawl swimming, both in pre and post-test. Swimming performance was assessed manually by a certified coach using a stopwatch (FINIS 3x100, Finis Inc., USA) and considered as the time taken (in s) to cover 25 m (T25). Swimming velocity (v25, in $m \cdot s^{-1}$) was calculated based on the ratio between the distance of 25 m and the T25. The stroke rate (SR, Hz) was assessed with a chrono-frequency meter (FINIS 3x300, Finis Inc., USA) from three consecutive stroke cycles between the 11th and the 24th m, and the stroke length (SL, in m) was estimated (SL = v / SR; Craig & Pendergast, 1979). The stroke index (SI, in $m^2 \cdot s^{-1}$) was computed (SI = v · SL; Costill et al., 1985) and the arm stroke efficiency (ηF, in %) was estimated based on the Froude efficiency (Zamparo et al., 2005).

Statistical analysis

The Shapiro-Wilk test was used to assess the normality of data. The mean and one standard deviation (M±1SD) were computed as descriptive statistics. Paired t-test with 95% confidence interval (95CI) was used to compare differences between pre- and post-tests in all variables. To compare differences between pre-PHV and mid-PHV, an unpaired t-test was used in each test (i.e., each moment). Cohen's d was selected as an effect size (d) and interpreted as: trivial if |d| < 0.2, medium if 0.2 > |d| < 0.5, and large if |d| ≥ 0.5 (Cohen, 1988). The percentage of variation (Δ) between tests was calculated ([pre-test – post-test] / [pre-test] · 100). All statistical analyses were performed using the SPSS software (v.27, IBM, SPSS Inc., Chicago, IL, USA) and GraphPad Prism (v.9, GraphPad Software, San Diego, CA, USA). The statistical significance was set at $p \leq 0.05$.

Results

Swimmers' MO was different between pre- and post-test (pre-test, −0.50±0.85 years vs post-test, −0.38±0.81 years; mean difference [95CI] = 0.12 [0.06 to 0.19], $t = 4.25$, $p < 0.001$). The effects of the off-season on anthropometry, in-water force, performance, and kinematics of all swimmers are presented in Table 1.

Table 1. Effects of six weeks off-season on swimmers (n = 18) anthropometrics, in-water force, performance, and kinematics.

Variable, units	Pre-test	Post-test	Mean difference (95CI)	t-test (p)	d	Δ
Anthropometrics						
Body mass, kg	50.47±7.61	52.49±7.59	2.02 (1.48 to 2.54)	7.98 (<0.001)	0.27	4.00
Stature, cm	162.66±8.36	163.82±8.01	1.16 (0.64 to 1.68)	4.72 (<0.001)	0.14	0.71
BMI, kg/m^{-2}	18.97±1.83	19.49±2.03	0.51 (0.31 to 0.73)	5.24 (<0.001)	0.27	2.74
Arm span, cm	165.41±10.37	166.49±10.31	1.08 (0.59 to 1.58)	4.62 (<0.001)	0.10	0.65
HSA D, cm^2	116.21±17.45	117.80±17.17	1.59 (0.97 to 2.21)	5.40 (<0.001)	0.09	1.37
HSA ND, cm^2	115.88±17.23	118.02±17.55	2.15 (1.35 to 2.94)	5.70 (<0.001)	0.12	1.85
In-water force and symmetry						
F_{PEAK} D, N	55.86±17.47	52.53±17.63	−3.33 (−10.00 to 3.35)	−1.05 (0.307)	0.19	−5.96
F_{PEAK} ND, N	57.79±22.63	55.16±17.68	−2.63 (−9.27 to 4.01)	−0.84 (0.415)	0.13	−4.55
SF_{PEAK} D, N	59.68±17.87	55.30±19.92	−4.38 (−13.14 to 4.37)	−1.06 (0.306)	0.23	−7.34
SF_{PEAK} ND, N	61.14±24.61	55.20±16.89	−5.94 (−13.49 to 1.61)	−1.66 (0.115)	0.28	−9.72
SyI, %	28.46±18.72	15.19±10.73	−13.26 (−24.23 to −2.30)	−2.55 (0.021)	0.87	−46.66
Performance and kinematics						
T25, s	16.19±1.47	16.18±1.35	−0.01 (−0.28 to 0.26)	−0.08 (0.935)	0.01	−0.07
v25, m·s^{-1}	1.56±0.14	1.56±0.13	−0.00 (−0.02 to 0.02)	−0.05 (0.962)	0.00	−0.03
SR, Hz	0.83±0.07	0.80±0.06	−0.03 (−0.07 to 0.01)	−1.56 (0.137)	0.46	−3.79
SL, m	1.88±0.12	1.95±0.16	0.07 (−0.01 to 0.16)	1.76 (0.097)	0.49	3.79
SI, m^2·s^{-1}	2.93±0.38	3.04±0.43	0.11 (−0.00 to 0.23)	2.07 (0.054)	0.27	3.85
ηF, %	23.58±1.62	24.02±1.86	0.44 (−0.68 to 1.56)	0.83 (0.420)	0.25	1.86

d, Cohen's d effect size; BMI, body mass index; D, dominant; HSA, hand surface area; ND, non-dominant; F_{PEAK}, mean peak force; T25, time; v25, swimming velocity; SR, stroke rate; SL, stroke length; SI, stroke index; ηF, Froude efficiency.

The MO of pre-PHV swimmers was −1.61±0.22 and −1.42±0.31 years, while for mid-PHV was 0.05±0.28 and 0.15±0.28 years in pre- and post-test (respectively). The comparison between pre-PHV (n = 6; 12.17±0.75 years old) and mid-PHV (n = 12; 13.33±0.65 years old) swimmers is shown in Figures 2-4. All anthropometric variables (Figure 2), F_{PEAK} ND (Figure 3, Panel B), SF_{PEAK} ND (Figure 3, Panel D), T25 (Figure 4, Panel A), and v25 (Figure 4, Panel B) were different between pre- and mid-PHV swimmers in pre-test. In post-test, all anthropometric (Figure 2) and in-water force variables (Figure 3, Panel A-D), as well as the SL (Figure 4, Panel D) and SI (Figure 4, Panel E) were different between groups.

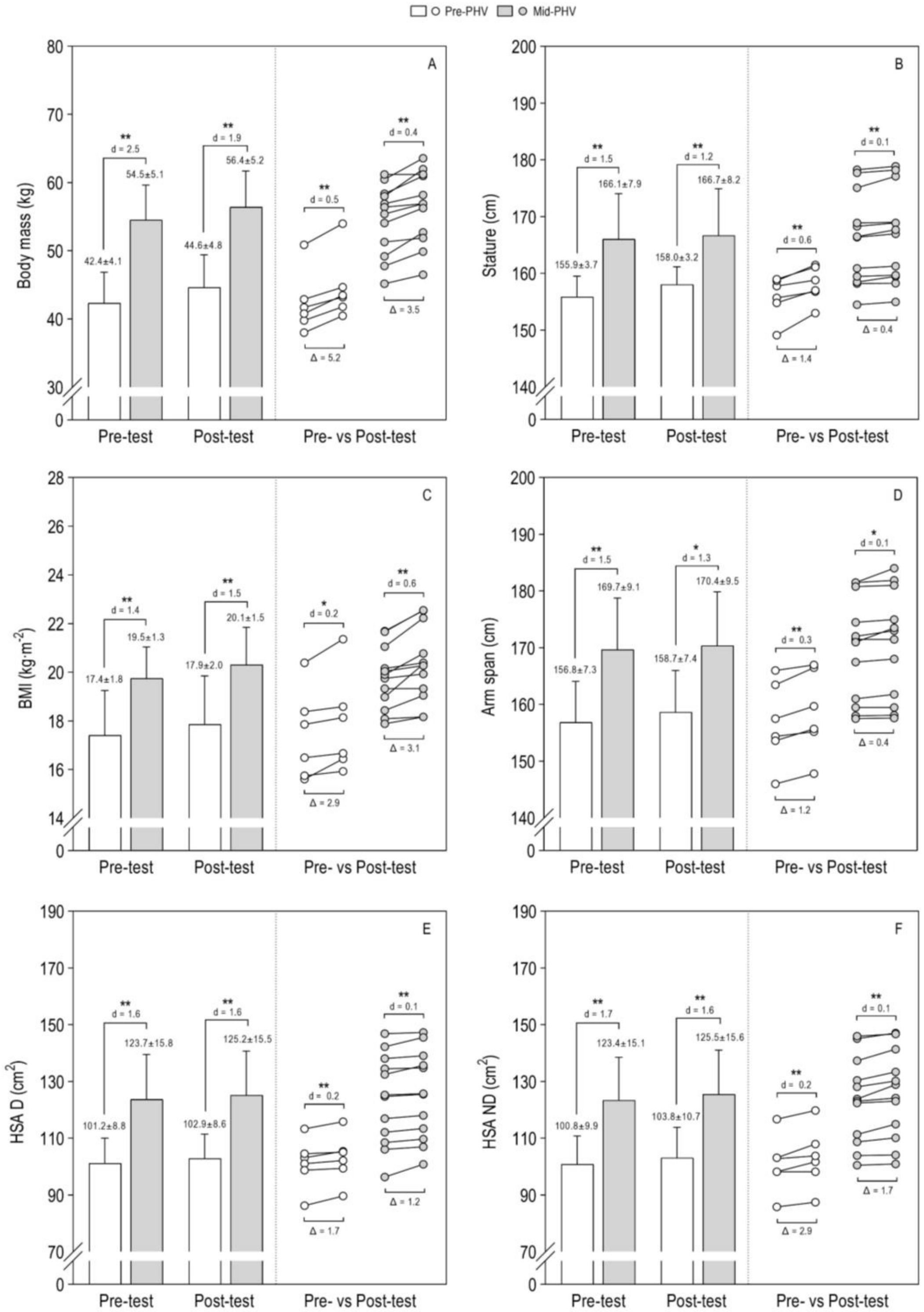

Figure 2. Effects of six weeks training cessation on swimmers' anthropometrics. White bars/dots represent pre-PHV swimmers' and light grey bars/dots represent mid-PHV swimmers. d, Cohen's d effect size; BMI, body mass index; D, dominant; ND, non-dominant; HSA, hand surface area. *, $p \leq 0.05$; **, $p \leq 0.01$

The changes on the anthropometrics over six weeks in pre-PHV and mid-PHV swimmers are shown in Figure 2. Pre-PHV swimmers changed the body mass (Panel A; mean difference [95CI] = 2.27 [1.63 to 2.90], $t = 9.22$, $p < 0.001$), stature (Panel B; mean difference [95CI] = 2.18 [1.04 to 3.32], $t = 4.92$, $p = 0.004$), BMI (Panel C; mean difference [95CI] = 0.44 [0.06 to 0.80], $t = 2.99$, $p = 0.030$), arm span (Panel D; mean difference [95CI] = 1.82 [0.96 to 2.67], $t = 5.45$, $p = 0.003$), HSA D (Panel E; mean difference [95CI] = 1.74 [0.53 to 2.96], $t = 3.68$, $p = 0.014$), and HSA ND (Panel F; mean difference [95CI] = 2.35 [0.50 to 4.20], $t = 3.26$, $p = 0.023$). In mid-PHV swimmers, changes were also found in the body mass (Panel A; mean difference [95CI] = 1.89 [1.09 to 2.69], $t = 5.25$, $p < 0.001$), stature (Panel B; mean difference [95CI] = 0.65 [0.31 to 0.99], $t = 4.19$, $p = 0.001$), BMI (Panel C; mean difference [95CI] = 0.56 [0.27 to 0.85], $t = 4.23$, $p = 0.001$), arm span (Panel D; mean difference [95CI] = 0.72 [0.15 to 1.28], $t = 2.79$, $p = 0.018$), HSA D (Panel E; mean difference [95CI] = 1.52 [0.67 to 2.37], $t = 3.93$, $p = 0.002$), and HSA ND (Panel F; mean difference [95CI] = 2.04 [1.04 to 3.05], $t = 4.49$, $p < 0.001$).

In-water force and symmetry (Figure 3) remained unchanged in both groups ($p > 0.05$). Performance and kinematics did not change in pre-PHV swimmers ($p > 0.05$), but changes were found in the mid-PHV group (Figure 4) for SR (Panel C; mean difference [95CI] = 0.06 [0.11 to 0.00], $t = -2.32$, $p = 0.040$) and SL (Panel D; mean difference [95CI] = 0.12 [0.00 to 0.23], $t = 2.29$, $p = 0.043$).

Discussion

The in-water force, performance, and kinematics did not decline after six weeks of training cessation in a group of competitive young swimmers. Despite the natural growth observed after the off-season (i.e., changes in anthropometrics), only the SR (–7.1% Δ) and SL (6.4% Δ) changed in the mid-PHV swimmers.

Body mass, stature, and therefore body limb length are anthropometric features that change with normal growth (Malina et al., 2004). After six weeks of training cessation, young swimmers were taller (1.2 cm) with a longer arm span (1.1 cm) and hand surface area (D: 1.6 cm^2; ND: 2.1 cm^2), but the magnitude of the effects was trivial. The growth spurt was more evident for hand surface area than for stature and arm span. Previous studies conducted with pre-pubertal swimmers (Tanner stages 1 and 2) observed differences in anthropometrics after 10 (Moreira et al., 2014) and 11 weeks (Morais et al., 2022) of training cessation. Body extremities' (i.e., hands and feet's) experienced accelerated growth during early stages of development, while a spurt in length or stature occurred later (Blanksby et al., 1986).

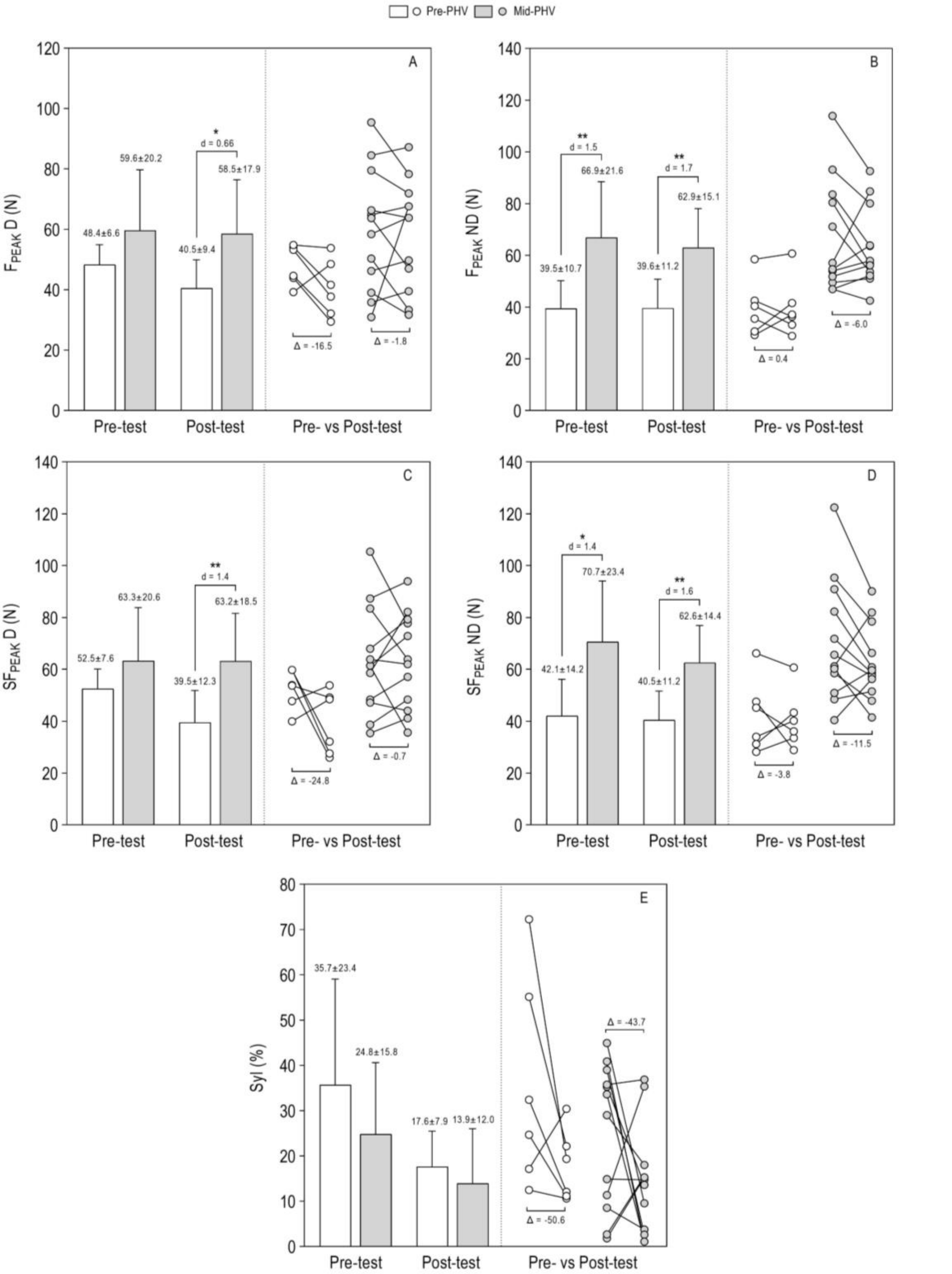

Figure 3. Effects of six weeks training cessation on swimmers' in-water force and symmetry. White bars/dots represent pre-PHV swimmers' and light grey bars/dots represent mid-PHV swimmers. d, Cohen's d effect size; F_{PEAK}, mean peak force; SF_{PEAK}, subsequent peak force; D, dominant; ND, non-dominant; SyI, symmetry index. *, $p \leq 0.05$; **, $p \leq 0.01$

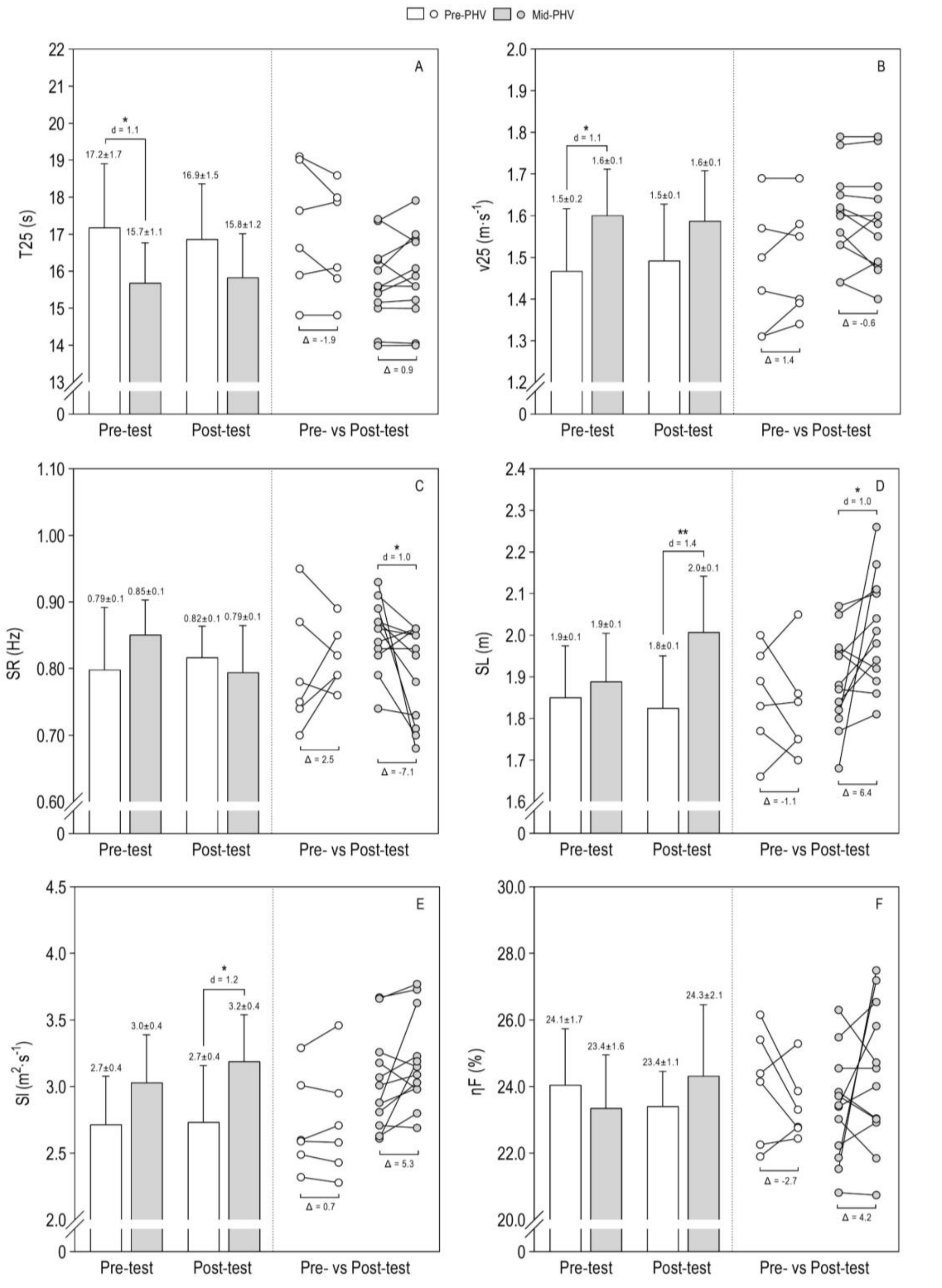

Figure 4. Effects of six weeks training cessation on swimmers' performance and kinematics. White bars/dots represent pre-PHV swimmers' and light grey bars/dots represent mid-PHV swimmers. d, Cohen's d effect size; T25, time; v25, swimming velocity; SR, stroke rate; SL, stroke length; SI, stroke index; ηF, Froude efficiency. *, $p \leq 0.05$; **, $p \leq 0.01$

For instance, greater body extremities variation was found after training cessation (Morais et al., 2022; Moreira et al., 2014). However, variations in body traits during circumpubertal years (–2 to +2 years of PHV) are fundamentally linked to growth maturation (Malina et al., 2004).

The growth spurts observed in the present study were related to the maturity offset, being more evident in pre-PHV swimmers than in their counterparts. Pre-PHV swimmers showed a tendency to have greater variation in HSA for both limbs (≈2-3% Δ) than in stature and arm span (≈1% Δ). Although mid-PHV swimmers demonstrate a similar trend for body extremities growth (≈1-2% Δ), the variation in stature and arm span tends to be lower (0.4% Δ). It can be argued that such variation (lower) is due to the positive MO of some swimmers, i.e., some reached or exceeded the PHV in the pre- or post-test. On the other hand, evidence referring to post-pubertal swimmers reported variations of 0.9% in stature and 0.2% or 0.7% in arm span after five (Ruiz Navarro et al., 2022) and four (Zacca et al., 2019) weeks of training cessation, respectively. In a way, the results of this study help coaches understand the variation of anthropometric traits according to maturity offset, helping them to interpret what to expect from their training group between the end of the season and the beginning of the new one.

The ability to apply force effectively in the water is a key factor in the forward displacement of swimmers' (Santos et al., 2021). After six weeks of a complete training cessation, swimmers were able to maintain the same behavior of F_{PEAK} in both limbs. Despite the negative variation between pre- and post-test (–5-6% Δ), swimmers' force was not impaired. The pattern of the upper-limbs in front-crawl derives mainly from shoulder adduction and internal rotation (Batalha et al., 2013). One study found that young swimmers (Tanner stages 1 and 2) were able to maintain upper-limbs strength by improving performance after interrupting the strength program during a normal swimming program (Garrido et al., 2010). At least for the younger population, muscle strength and size can be maintained for up to 32 weeks if a strength session is guaranteed with relative load maintenance (Spiering et al., 2021). It is common for young swimmers to be physically active during school schedules and summer/winter holidays. The contribution of non-swimming physical activities may offset the effects of training cessation, at least for the in-water force production. Notwithstanding, a different trend was described for another cohort of swimmers (Neufer et al., 1987; Ruiz-Navarro et al., 2022). Male post-pubertal swimmers (MO: 3.41±0.86 years) were impaired in mean swimming forces after five weeks of training cessation (Ruiz-Navarro et al., 2022). The authors argued that such variation might be related to energy contributions rather than neuromuscular capacity. Impairments were also found in college male swimmers after four weeks of training cessation, as the ability to apply force (swimming power) measured with tethered swimming declined by 13.6% (Neufer et al., 1987). So, it can be argued that the effects of training cessation on swimming kinetics are dependent on the chronological age, and therefore MO.

A greater detraining effect on dry-land strength variables has been linked to pre-PHV boys when compared to mid- and post-PHV (Meylan et al., 2014). The findings of the present study revealed that neither pre-PHV swimmers nor mid-PHV were affected after the training cessation, but the behavior of the in-water forces seems to be highly dependent on MO mainly in the post-test. Evidence suggests that the spurt in muscle strength occurs about 1.5 years before PHV and the peak is reached after PHV (>0.5 years; Beunen & Malina, 1988). In fact, pre-PHV swimmers were able to apply ≈40 N in the post-test, while mid-PHV swimmers showed a value of ≈61 N (D: ≈59; ND: ≈63 N). Thus, such differences with large effects can be attributed to natural growth. Therefore, coaches and researchers must be aware of the diversity in biological maturation within the group, which can lead to different behaviors in applied force and, therefore, in swimming performance.

Although the effects of training cessation on forces are still scarce, the same applies to SyI. A tendency to obtain a more similar force pattern in both upper-limbs (–46.7% Δ, large effects) was shown after training cessation. It can be stated that a competitive season or a full macrocycle can lead to a more asymmetric stroke due to the breathing pattern used. Choosing to breathe unilaterally (most frequent breathing pattern) can trigger the application of more force on the contralateral side (Tourny-Chollet et al., 2009). At least for shoulder rotators, a full competitive season seems to favor muscular imbalances (internal vs external rotation) in young swimmers (Batalha et al., 2013) However, in regard to in-water forces, this imbalance seems to attenuate from the end of a competitive season to the beginning of the next one.

Deterministic models point out that muscular strength and anthropometrics can influence technique and, therefore, performance (Barbosa et al., 2010). The kinematics did not change in pre-PHV swimmers but decreases in SR were found in the mid-PHV group. At earlier ages, the development of SR is a challenge due to the muscle properties of swimmers. As such, the ability of these swimmers, even in mid-PHV stage, to maintain SR is limited, and this type of SR reductions should be expected over detraining, mainly due to loss of water sensitivity. However, the same did not happen with SL, in which increases in the mid-PHV group were found. This is in agreement with previous studies in which increases in SL after detraining were dependent on growth, mostly related to the development of arm span (Moreira et al., 2014).

The SR and SL combination defines swimming velocity in young swimmers. Based on this specific behavior, v25 remained unchanged for both maturational groups. Even so, the mid-PHV group was able to show greater efficiency (given by the SI) in the post-test. This means that swimming performance and efficiency are not impaired by a training cessation, at least for such a short distance (25 m). Moreira et al. (2014) found an increase in v25 and SI in pre-pubertal swimmers (Tanner stages 1 and 2) during a summer break. However, contradictory findings have been reported for longer distances such as 50m (Ruiz-Navarro et al., 2022), 100m (Morais et al., 2022; Sambanis, 2006), 200m (Fiori et al., 2022), and 400m (Zacca et al., 2019) front-crawl. The underlying cause of these mixed findings may be the swimmers' stage of development. If young swimmers are reaching a more adult-like swimming profile, some impairments will start to be seen due to the growth spurts that will not occur as often (Ruiz-Navarro et al., 2022; Zacca et al., 2019).

Some limitations can be acknowledged in the present study. The amount of non-specific physical activity was not controlled during detraining, although some verbal cues were provided to the participants. Biological maturation was assessed by an indirect method and interpreted with swimmers' sex pooled together. So, future studies are necessary to deeply understand the role of long-term changes on in-water forces and the effect of biological maturation in the same competitive age-group. Dividing the data according to the swimmers' gender (i.e., maturity offset treatment in cohorts of girls and boys) can also be beneficial for tracking swimmers' long-term development and reviewing competition policies (if necessary).

Practical Applications

Daily swim training is characterized by mixed participation (i.e., boys and girls training together). In this context, natural growth and biological maturation play an important role in defining the degree of change to which swimmers will be exposed. These types of "internal" changes have an impact on how swimmers go through a specific training period. Although swimming training can be interrupted for six weeks, there is a chance of maintaining in-water force, performance, and kinematics in young competitive swimmers. The present work helps coaches to have a clearer view of how they should interpret different developmental rates of swimmers belonging to the same group. Consequently, it gives new insights into how performance-related parameters evolve over the detraining period in distinct maturational groups that share the same environment. Thus, the interpretation of training effects based on the determination of the swimmer's PHV should start to be a common practice among the community of swimming coaches.

Conclusion

A six-week training cessation does not reduce the in-water force, performance, and kinematics of young competitive swimmers. Natural growth was experienced by swimmers throughout the detraining period, being more evident in pre-PHV swimmers. Maturity status seems to interact with most of the selected parameters.

Chapter 5. General Discussion and Conclusion

The main aim of this thesis was to analyze the changes in force production of young competitive swimmers (girls and boys) during a full season and over a detraining period. Simultaneously, the usefulness of a two-hand pressure system was tested to understand if the system was a friendly tool to be used in training control and assessment in-water forces. Our findings suggested that the scientific body knowledge about long-term changes in force production remains little explored and even inexistent in young swimmers. The two-hand pressure system showed to be a reliable setup to measure in-water forces, and not induced any mechanical or efficiency constraints at front-crawl. However, to get data comparable with other methods (as tethered-swimming), a correction factor must be applied. While a full competitive season allows improvements in swimmers force production, a six-week detraining period not affects in-water forces in a cohort of young swimmers.

The starting point of this thesis was to conduct a systematic review based on direct methods that are regularly used to measure propulsive forces in human competitive swimming (Study 1). Our research concluded that the values of the propulsive force are dependent on the assessment methods, swimming strokes/segmental actions, swimmers' characteristics, and training settings. Tethered-swimming and differential pressure sensors became the easiest and most reported methods to measure in-water forces. Tethered swimming has been the most frequently used (82.9%), while differential pressure systems presented a recent boost of interest (2015-2020: 17.1%). Due to the 'nature' of the assessments, both methods showed a trend for different mean and peak forces. Although tethered swimming has been suggested as a reliable method (Amaro et al., 2014), it remains unanswered whether the results from a stationary effort are more representative than those conducted in a free-swimming condition (i.e., with pressure sensors) without stroke constraints. Thus, a reliability of pressure sensors and an agreement between both methods would help coaches to acquire reliable data and compare that with the setup available on their swimming squad whether that be tethered swimming or pressure sensors. Despite the men are able to apply higher forces than women counterparts, a gap in the state of the art remains while testing boys and girls. So, link the growth and biological maturation process to in-water forces adaptations would help to get deeply insights on long-term changes. Furthermore, the available longitudinal studies were mainly focused on the effect of dry-land training (e.g., Amaro et al., 2017), tapering (Neufer et al., 1987), warm-up (e.g., Neiva et al., 2011), or propulsion devices (A. C. Barbosa et al., 2013) from 1 up to 10 weeks. Therefore, until now, no study was able to provide deeper insights into how propulsive forces change within or between competitive seasons in response to an annual training periodization. To fulfil some gaps, experimental studies on assessment tools for training control and optimization (Studies 2, 3, and 4) and long-term follow-ups on force production in young swimmers (Studies 5 and 6) were conducted.

Researchers and coaches seek to understand training effects and identify the main determinants for performance enhancement (Hopkins et al., 1999). Thus, performance testing and monitoring while having the impact of internal and external load should resemble as closely as possible to a real background (Currell & Jeukendrup, 2008). The validity, reliability and sensitivity of devices/apparatus or measures are crucial to have an accurate performance control (Atkinson & Nevill, 1998; Hopkins, 2000). Some research within the swimming topic has already established agreements between different methods (Barbosa et al., 2015; Barbosa et al., 2018) and verified their reliability (Amaro et al., 2014; Conceição et al., 2018; Nagle Zera et al., 2021), as well as tried to understand its impact on swimming mechanics (Barbosa et al., 2010; Conceição et al., 2013; Ribeiro et al., 2016). Ensure high levels of validity and reliability avoid measurement errors or inter-individual differences that do not reflect the real context of practice (Hopkins et al., 1999). Such approaches become even more relevant if devices/apparatus are needed on long-term testing on changes within and between competitive seasons. Thus, previously to understand intra-swimmers' variation (i.e., longitudinal changes), a validation (Appendix I), an agreement between methods (Study 2) identified in a recent systematic review (Study 1), and a reliability (Study 3) were conducted to mitigate measurement errors. The mechanical and efficiency constraints when swimming front crawl were also analyzed (Study 4).

Although there is still no consensus on a gold standard method for measuring in-water forces, the existent tools should mimic as much as possible the movement pattern of the body limbs (T. M. Barbosa et al., 2020). In tethered-swimming, the swimmer remains connected to a load cell/strain gauge without forward displacement (Yeater et al., 1981). Then, the sum of all forces acting on the body can be measured during a segmental or a full-body condition (Mourouço et al., 2010). This method appears to sustain the swimmer's strength potential rather than the ability to apply force effectively (Ruiz-Navarro et al., 2020), leading to a data overestimation (Samson et al., 2018; Study 2). Using a flume with water flow at a given velocity (Ruiz-Navarro et al., 2022) can help to overcome this issue (i.e., absence of drag). However, this kind of hard and highly cost setup may not be available in all competitive squads (Mooney et al., 2016). On the other hand, pressure sensors allow a displacement throughout the water in a condition similar to "free-swimming" (Study 1). It measures the water pressure differences between the palmar/plantar surface (low-pressure field) and dorsal surface (high-pressure field) during an unsteady motion. So, the two-hand sensors system measures the resultant force of the hand rather than the effective propulsive force (Study 3). Despite this, due to the easy-to-use procedure without encompassing a heavy setup, pressure sensors can be more suitable to get swift and real-time feedback in longitudinal designs (Studies 5 and 6) contrarily to other methods. In fact, pressure system (Aquanex System) demonstrated to be a valid (Appendix I) and reliable setup (Study 3) to obtain in-water forces in young competitive swimmers. Plus, the system seems not to induce constraints on the mechanics and efficiency of young swimmers (Study 4), which can allow coaches to use it on their daily-basis (Appendix V). Despite that, coaches and researchers are advised to take some care in its application, as the initial swimmer velocity can be compromised probably due to the system cable design. Still, this reinforces the idea that the use of pressure sensors remains the assessment method that most closely resembles "free swimming" and can be used to monitor kinetic changes over time. Furthermore, in-water force of young competitive swimmers relies on different assessment methods, as tethered swimming presents higher values of force compared to pressure sensors (Study 2). Within this, correction factors are recommended for an accurate data comparison.

Young swimmers' performance relies on a multifactorial and dynamic phenomenon, where anthropometrics and biomechanical characteristics define the energetic profile and may contribute to performance enhancement (Morais et al., 2021). Research on young swimmers has been largely focused on such parameters mainly through cross-sectional research designs. However, such designs are less comprehensive and informative than the longitudinal ones (Costa et al., 2012). Thus, longitudinal data allows to track the swimmers' performance-related parameters (Costa et al., 2010) and understand the cause-and-effect relationships over the competitive season and off-season training (Zacca et al., 2019), to predict their performance throughout a given time of period (Costa et al., 2010), and to help coaches to achieve realistic training goals (Pyne et al., 2001). So, monitoring the changes over time can provides fundamental insights into the performance improvements and the long- or short-term training effects (Costa et al., 2010).

The lack of in-depth knowledge on long-term changes in young swimmers seems arise from some ethical issues when children are evaluated and also due to determinists models that emphasize other domains (Study 1). Thus, assessments at so early ages should be less expensive, invasive, complex or time consuming (Barbosa et al., 2010).

According to the literature review (Study 1), longitudinal studies focusing on force production were conducted in mature swimmers' and had a short time frame. While this could give important clues on specific regular swimming tasks as warm up (Neiva et al., 2011), tapering (Neufer et al., 1987) or propulsion devices (A. C. Barbosa et al., 2013), it may restrict the interpretation on how a training periodization influences the force production. Young swimmers typically undergo an annual traditional training periodization with two or three peak forms (i.e., macrocycles) followed by detraining period between 4 and 11 weeks (Morais et al., 2022; Zacca et al., 2019). It is expected that growth spurts usually may occur within a competitive season in a group of young swimmers (Abbott et al., 2021), and these can lead to changes in performance (Morais et al., 2022). Moreover, the longer the time frames under analysis, the greater is the possibility to observed larger improvements (Costa et al., 2012). After 48 weeks (Study 5), young swimmers are able to increase in-water forces (16-24% Δ) and performance (8% Δ) being more evident in the first months of the season (i.e., first macrocycle; Appendix II). Despite the natural growth (i.e., increase in anthropometrics traits), only the stroke index changed between the beginning and the end of the season, translating into a more efficient swimming pattern. On the other hand, in-water forces, performance, and kinematics remained unchanged after six weeks of detraining (Study 6). A natural growth was experienced by swimmers throughout the detraining period, being more evident in pre-PHV swimmers. Pre-PHV swimmers were able to apply ≈40 N, while mid-PHV swimmers showed a value of ≈61 N (D: ≈59; ND: ≈63 N) after six weeks o detraining.. So, the maturity status seems to interact during the training cessation. In addition, a higher contralateral asymmetric motion (i.e., higher SyI) was found at the end of the season (Study 5 and Appendix III). Still, the degree of imbalance (−46.7% Δ) seems to dissipate after the summer break (Study 6 and Appendix III).

As the main conclusions it can be stated that although there is no gold standard method to measure in-water forces, pressure sensors are an easy-to-use and reliable method to be used in training control and optimization. Despite this, a correction factor should be applied when different methods are considered. The in-water force of young swimmers improves within a competitive season without showing a substantial and harmful decrease after a detraining period. In addition, swimmers' maturity status interacts with the training cessation fluctuations.

Chapter 6. Suggestions for future research

The current thesis provides an original approach and opens a new path for further studies that want to focus on practical evidence. Thus, suggestions for future research are listed below:

- Monitor in-water force within and between competitive seasons considering other specific training regimes (e.g., dry-land training) and understand the transfer between dry-land strength and in-water forces and performance.
- Provide deeper insights into how the biological maturation influences the performance-related variables and consider direct methods to measure it;
- Perform longitudinal approaches in elite and masters' swimmers and understand the in-water force variability throughout a competitive season.
- Analyze the in-water forces in more than one swimming stroke and clarify the relationship between the force production and performance;
- Characterize the force profile according to the underwater pathways of each limb and consider other force parameters (e.g., impulse);
- Clarify how in-water forces change according to expertise (i.e., competitive level) in a broad range of velocities;
- Apply different strength training programs (dry-land training with free-weights, elastics and in-water training) and understand their effect on the in-water forces;
- Understand the short and long-term changes in force with propulsion and add-resistance training materials (e.g., parachute; Appendix V).

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Appendix I

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Appendix II

Morais, J. E., Barbosa, T. M., Forte, P., Silva, A. J., & Marinho, D. A. (2021). Young Swimmers' Anthropometrics, Biomechanics, Energetics, and Efficiency as Underlying Performance Factors: A Systematic Narrative Review. *Frontiers in Physiology*, 12, 691919.

Appendix III

Bartolomeu, R. F., Rodrigues, P., Santos, C. C., Costa, M. J., & Barbosa, T. M. (2021). Is There Any Effect of Symmetry on Velocity of the Four Swimming Strokes? *Symmetry*, 14(1), 12.

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Appendix VI

Batalha, N., Parraca, J. A., Marinho, D. A., Conceição, A., Louro, H., Silva, A. J., & Costa, M. J. (2021). The Acute Effects of a Swimming Session on the Shoulder Rotators Strength and Balance of Age Group Swimmers. International *Journal of Environmental Research and Public Health*, 18(15), 8109.

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Appendix V

Robinson, R. O., Herzog, W., & Nigg, B. (1987). Use of force platform variables to quantify the effects of chiropractic manipulation on gait symmetry. *Journal of Manipulative Physiology Therapy*, 10(4), 172-176.

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Appendix I

Validation of a differential pressure system to assess in-water forces in competitive swimming

Abstract

The aim of this study was to validate a differential pressure system to assess in-water forces in competitive swimming. One of two hand sensors (Type A) that compose the differential pressure system (Aquanex v.4.1, STR, USA) was placed inside a wind tunnel (Axial Propellor Fan, England), considered the gold standard. A frequency inverter was used to control the twenty-two frequencies. The mean force (F_{MEAN}, N) acting on the sensor and in the model of the wind tunnel was measured. To consider a valid method, the following criteria were analyzed: (i) paired t-test ($p>0.05$); (ii) simple linear regression models ($R^2 \geq 0.49$); and (iii) Bland-Altman plots (at least 80 % of the plots within the limits of agreement). The results showed no differences between both methods ($p=0.884$). Furthermore, a significant association with a high effect ($R^2=0.573$, $p<0.001$) was found, as well as a small bias (0.002 N) between the two methods. Thus, the differential pressure system seems to be valid to assess the in-water forces as it met all the validation criteria.

Key words: pressure sensors, force, swimming.

Santos., C. C., Costa., M. J., Marinho, D. A., Barbosa, T. M., & Rosa, S. M. (accepted). Validation of a differential pressure system to assess in-water forces in competitive swimming. Proceedings of the 13th World Congress of Performance Analysis of Sport & 13th International Symposium on Computer Science in Sport. *Advances in Intelligent Systems and Computing*.

Introduction

Swimming performance is mainly dependent on the swimmer's capacity to over-come water resistance by applying effectively propulsive force in water. The assessment of such forces in competitive swimming is a key aspect of training control (Santos et al., 2021). In the last couple of years, the in-water force assessment (i.e., the forces acting in the direction of swimmer displacement) has been done using a differential pressure sensor system (i.e., Aquanex System). This is a set-up that allows the displacement of the swimmers without any constraints in stroke mechanics and efficiency in front crawl (Santos et al., 2022a). Furthermore, allows getting swift and real-time feedback for swimming coaches and researchers tracking-down the in-water force data (Santos et al., 2021) with accuracy (Santos et al., 2022b). Despite this, as far as our understanding goes, the system lacks a validation. Although still there is no consensus on a gold standard for measuring the in-water forces, the wind tunnel has been used in cyclic sports (Bäckström et al., 2016). Therefore, the aim of this study was to validate a differential pressure system through the wind tunnel. It was hypothesized that the Aquanex System would meet the validation criteria to assess in-water forces in competitive swimming.

Methods

Experimental design

A differential pressure system (Aquanex v.4.1, Model DU2, Swimming Technology Research, Richmond, USA) was placed inside a subsonic open-circuit suction type wind tunnel (Axial Propellor Fan, Armfild Limited, England), as gold-standard. One sensor (Type A) was fixed vertically with a rigid iron and oriented to the cone at the base of the test section in the wind tunnel. The sensor was attached to a two-channel A/D converter connected to a laptop with the Aquanex software (Santos et al., 2021) and properly calibrated (force equal to zero). The force output (in Newton, N) acquired with the system is derived by multiplying the pressure by the area (Santos et al., 2022b). To measure the mean force (F_{MEAN}, N) of both methods, the air was sucked through the test section by the fan located at the rear of the wind tunnel. Twenty-two frequencies (i.e., velocities) were controlled through a frequency invertor (DV-700, Panasonic, Osaka, Japan) starting at 12Hz and increasing by 2Hz, up to 54Hz. Afterwards, the F_{MEAN} acting on the sensor at each velocity was obtained by considering the frontal area of the sensor.

Statistical analysis

The normality and homoscedasticity of the data were checked using the Shapiro-Wilk and Levene tests, respectively. The mean and one standard deviation (M±1SD) were computed as descriptive statistics. A paired sample t-test was used to compare the variables between both methods. Simple linear regression models between both methods were computed for all variables. As a rule of thumb, effect sizes were interpreted as: (i) very weak if $R^2 < 0.04$, weak if $0.04 \geq R^2 < 0.16$, moderate if $0.16 \geq R^2 < 0.49$, high if $0.49 \geq R^2 < 0.81$, and very high if $0.81 \geq R^2 < 1.0$ (Barbosa et al., 2011). The Bland-Altman plots with 95% limits of agreement (LoA) were used to display the systematic differences between the two methods. The bias (mean difference), standard deviation (SD), and upper and lower LoA were calculated (Bland & Altman, 1986). The validation was analyzed considering the three validation criteria, as previously reported (Barbosa et al., 2011): (i) paired t-test (p>0.05); (ii) simple linear regression models ($R^2 \geq 0.49$); and (iii) Bland-Altman plots (at least 80 % of the plots within the LoA). All statistical analyses were performed in the SPSS software (v.27, IBM, SPSS Inc., Chicago, IL, USA) and GraphPad Prism (v.9, GraphPad Software, San Diego, CA, USA).

Results

No differences in F_{MEAN} were found when comparing the differential pressure system (i.e., Aquanex System) and the wind tunnel (Aquanex System: 0.250±0.087 N, wind tunnel: 0.244±0.086 N; p=0.884). Linear regression models between both methods presented showed significant associations with a high effect (R^2=0.573, p<0.001) for F_{MEAN} (Figure 1). The Bland-Altman method reveal that more than 80% of the plots were within the upper and lower LoA (Figure 2) and the bias was small (0.002 N).

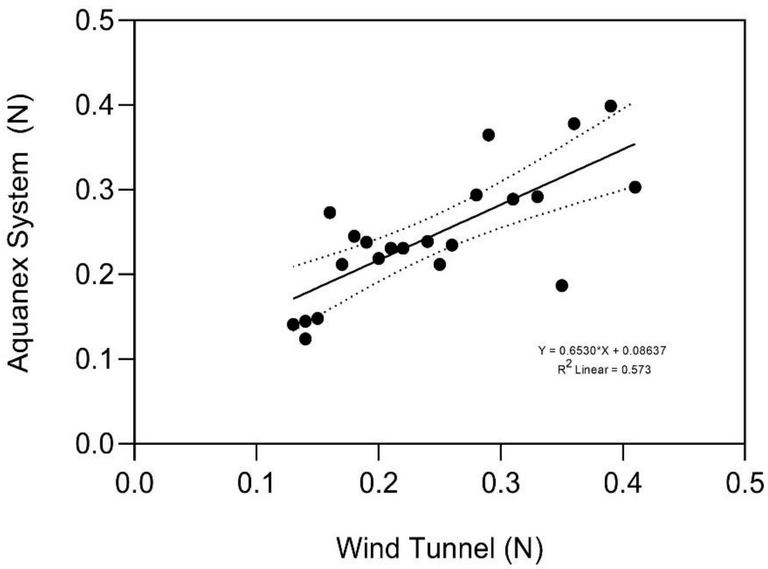

Figure 1. Scattergram with the main trendline (solid line), 95% confidence interval (dotted lines), and determination coefficient (R^2). N, newton; F_{MEAN}, mean force.

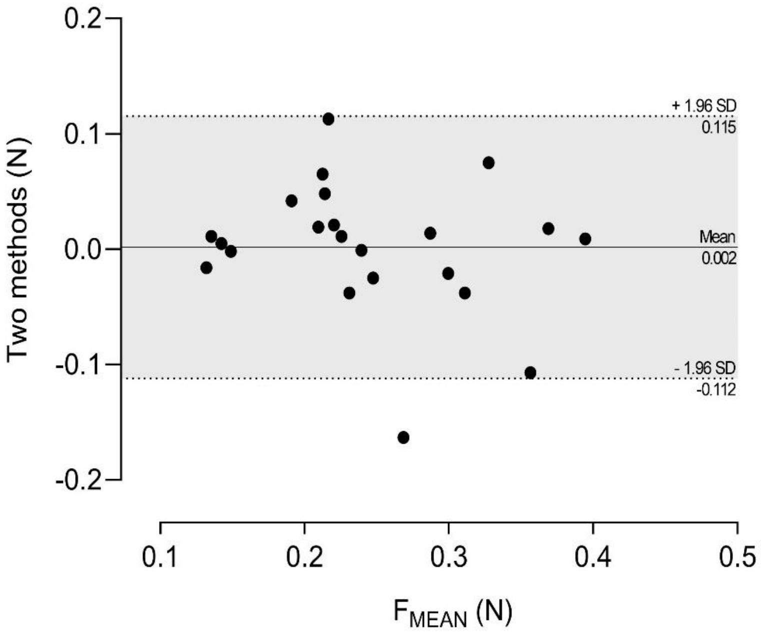

Figure 2. Bland-Altman plots of the difference between Aquanex System and Wind Tunnel (y-axis) and mean of measurements (x-axis). Dotted lines represent the upper and lower 95% LoA (mean differences ± 1.96 SD of the differences) and solid lines represent the mean differences between the two methods (bias). N, Newton; F_{MEAN}, mean force.

Discussion and Conclusion

The differential pressure system accomplished the three validation criteria. Some biases were found between the two methods, and this might be explained by the "nature" of the assessments and the interaction of the different fluids' characteristics. This means that the sensors can be highly sensitive to the air velocity while remaining a pressure absence (which does not happen in the water). Furthermore, the mean values were lower than those retrieved from a regular basis assessment conducted in a more ecological valid environment (i.e., water; Santos et al., 2021). Still, this is the first step to validate the usefulness of a two-hand pressure system for in-water force measurements. Future studies should try to use a water channel to check the validity for the Aquanex System in a broad range of variables (e.g., peak force or higher velocities). Despite this, the differential pressure system (Aquanex System) seems to be valid to assess the in-water forces in competitive swimming.

Appendix II

Follow-up of young swimmers' kinematics and kinetics during the winter season macrocycle

Introduction

Monitoring changes of performance predictors over time can provide fundamental insights about the effectiveness of the training process. Young swimmers are susceptible to those changes more than any other cohort of swimmers (Morais et al., 2021). However, there is a lack of research on how kinetic aspects may change between the first months of the season. Thus, the aim of this study was to analyse and compare the kinetics and kinematics of young swimmers between two moments of the winter season macrocycle.

Methods

Ten young swimmers (7 boys and 3 girls) were recruited at the beginning of the competitive season and completed two assessment moments (September, M1; December, M2) corresponding to the full traditional winter season macrocycle. The body mass (BM, in kg) and height (in cm) were assessed with a scale (TANITA, BC-730, Amsterdam, Netherlands) and a digital stadiometer (SECA 242, Hamburg, Germany), respectively. The hand surface area (HSA, in cm^2) for both hands was measured with photogrammetry. The in-water hand resultant force, reported as propulsive force (PF, in N), during the 25-m front crawl (maximal bout) was measured with a differential pressure system (Aquanex 4.1, STR, USA) allowing retrieve PF values for the dominant (PF_D) and non-dominant (PF_{ND}) hand. The swimming velocity (v, in $m \cdot s^{-1}$) was calculated based on the ratio between the distance and time to complete 25m (T25). The stroke rate (SR, in Hz) was assessed with a chrono-frequency meter (FINIS 3x300, Finis Inc., USA) from 3 consecutive stroke cycles between 11th and 24th meter. Therefore, the stroke length (SL, in $m \cdot c^{-1}$) and stroke index (SI, in $m^2 \cdot c^{-1} \cdot s^{-1}$) were estimated as: $SL = v/SR$; $SI = v \cdot SL$. The paired sample t-test was used to compare moments in all variables and Cohen's d was selected as an effect size (d) being interpreted as trivial if $|d| < 0.2$, medium if $0.2 > |d| < 0.5$, and large if $|d| \geq 0.5$.

Results

No differences were found in age between M1 and M2 (M1: 12.20±0.79, M2: 12.40±0.70, p=0.17, d=0.27). The comparison between moments for anthropometric, kinematic, and kinetic domains were shown in Table 1. The height, HSA D, HSA ND, T25, v25, SI and PF_{ND} were significantly different ($p \leq 0.05$) between M1 and M2

Table 1. Mean ± standard deviation (SD) for the anthropometric, kinematic and kinetic domains of young swimmers.

D	Variables	M1	M2	*p*	d
Anthropometric	BM (kg)	49.06±7.94	49.19±6.99	0.83	0.02
	Height (cm)	157.35±8.52	159.34±8.51	<0.01	0.23
	HSA D (cm^2)	105.05±13.62	113.49±16.65	<0.01	0.55
	HSA ND (cm^2)	107.25±11.36	114.46±11.48	<0.01	1.79
Kinematic	T25 (s)	17.63±1.35	16.46±1.40	<0.01	0.85
	v25 ($m \cdot s^{-1}$)	1.43±0.11	1.53±0.13	<0.01	0.83
	SR (Hz)	0.79±0.10	0.80±0.06	0.76	0.12
	SL ($m \cdot c^{-1}$)	1.83±0.27	1.92±0.18	0.34	0.39
	SI ($m^2 \cdot c^{-1} \cdot s^{-1}$)	2.61±0.47	2.94±0.47	0.04	0.70
Kinetic	PF_D (N)	53.65±12.94	58.96±15.04	0.14	0.38
	PF_{ND} (N)	52.37±9.51	66.04±15.87	<0.01	1.04

D, domain; BM, body mass; kg, kilogram; HSA, hand surface area; cm, centimeter; D, dominant; ND, non-dominant; M1, moment 1; M2, moment 2; T25, time of 25m; v25, velocity of 25m; s, second; SR, stroke rate; Hz, Hertz; SL, stroke length; SI, stroke index; N, Newton; $m \cdot c^{-1}$, meter per cycle; $m \cdot s^{-1}$, meter per second; PF_D, propulsive force of dominant hand; PF_{ND}, propulsive force of non-dominant hand.

Conclusion

A full winter training macrocycle seems to induce changes in kinematics and kinetics of young swimmers. There was a performance improvement even with maintenance in stroke mechanics (i.e., SR and SL). That improvement was accompanied by an increment (≈14 N) in the PF_{ND} which may be translated in a more economical swimming corroborated by the significant increase in the SI.

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Appendix III

Changes in force and symmetry of young swimmers over a full competitive season and training cessation

Introduction

The ability to apply force in the water is a key-factor in forward displacement. Swimmers should exert a similar contralateral force to diminish drag and enhance performance. While an asymmetric motion was shown in all swimming strokes for mature swimmers (Bartolomeu et al., 2022), the fluctuation over time in force and symmetry remains unknown. The current study aimed to analyze the effects of a competitive season and detraining in force and symmetry.

Methods

Nine young swimmers, six boys and three girls (12.0±0.8 years, 48.1±8.5 kg of body mass, 156.6±7.9 cm of height), were evaluated over a competitive season followed by detraining (i.e., five testing moments; M_i): M_1: September; M_2, December; M_3, April; M_4, July; M_5, September After a standardized warm-up, swimmers were instructed to perform two maximum repetitions of 25 m at front crawl (full-body). In-water force was measured using a reliable differential pressure system (Santos et al., 2022) composed by two hand sensors (Aquanex 4.1, STR, USA). The subsequent peak force (SF_{PEAK}, in N) for the dominant (D) and non-dominant (ND) hand was defined as the peak value obtained in each two subsequent force-time curves at the 11th m. The symmetry index (SyI, %) was calculated and interpreted as reported elsewhere (Bartolomeu et al., 2022). Repeated measures ANOVA followed by the Bonferroni *post-hoc* test was computed to analyse the variation between the M_i ($p \leq 0.05$). The percentage of variation (Δ) between M_i was also considered.

Results

The effects of the full competitive season and training cessation on in-water force and symmetry are presented in Table 1. A time effect was found in SF_{PEAK} D and SyI (ΔM_4-M_5 = 69.86%).

Table 1. Effects of the M_i on in-water force and symmetry.

	Time effect		Moments				
	F	p	M_1	M_2	M_3	M_4	M_5
SF_{PEAK} D, N	2.78	0.04*	48.8±14.6	54.2±15.4	55.6±17.9	65.8±22.3	53.4±23.3
SF_{PEAK} ND, N	1.38	0.26	46.4±7.9	57.3±14.1	58.7±21.5	57.1±31.3	54.3±21.3
SyI, %	5.08	0.00*	14.6±13.3	18.6±12.9	23.9±13.6	35.5±20.1	10.7±5.6†

*, p≤0.05; † differences between M_4-M_5.

Discussion

Younger swimmers' force remains similar throughout a full competitive season followed by training cessation. An annual training plan training seems to impose an increase in the SyI (i.e., asymmetric motion), while a more symmetric motion is seen after training cessation.

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Appendix IV

How much strength the young competitive swimmers are able to transfer from dry land to water? A pilot study

Introduction

Propulsive force plays a major role in the swimming performance being produced mainly by the upper limbs through the shoulder internal rotation (IR). While the shoulder rotators´ strength has been widely investigated in young competitive swimmers, the propulsive force mechanism retained little attention (Santos et al., 2021). Moreover, to our best knowledge, there is not any study aimed to quantify the relative force transfer (RFT) from land to in-water actions. Thus, the aim of this study was to analyze the RFT from land to water in young swimmers at the front-crawl stroke.

Methods

Eleven young swimmers, eight boys and three girls (12.00±0.60 years, 49.95±7.19 kg of body mass, 156.41±8.26 cm of height and 263±56.78 FINA POINTS in 50-m freestyle short course), were recruited at the beginning of the competitive season. Dry land strength variables were measured with a digital handheld dynamometer (microFET®2, Hoggan Scientific, USA) allowing to retrieve the isometric peak strength of shoulder internal rotator (in Newton, N) for the dominant (IR_D) and non-dominant (IR_{ND}) upper limbs. All swimmers underwent a 10-min warm-up, followed-up by a familiarization set (one set of two submaximal and one maximal repetition by each limb). Subsequently, the data were collected from two maximal IR repetitions, as described elsewhere (Batalha et al., 2021). The highest value was considered for further analysis. The in-water propulsive force (N) at a 25-m front crawl (maximal bout) was measured with a differential pressure system (Aquanex 4.1, STR, USA) and values for the dominant (PF_D) and non-dominant (PF_{ND}) upper limbs were retrieved as previously reported (Morais et al., 2020). The RFT (in %) was calculated for both limbs as: $RFT_D = [(100*PF_D)/(IR_D)]$; $RFT_{ND} = [(100*PF_{ND})/(IR_{ND})]$. The paired sample t-test was used to compare the upper limbs in all variables.

Results

Dry land strength was significantly higher when compared to in-water propulsive force in dominant (IR_D: 92.55±20.88 N, PF_D: 38.65±7.33 N; p<0.01) and non-dominant (IR_{ND}: 87.60±23.02 N, PF_{ND}, 37.16±6.16 N; p<0.01) upper limbs. No differences were found when comparing upper limbs at the same environment. The RFT on water based on dry-land assessment was 43.58±12.19 % and 44.30±11.15 % for the dominant and non-dominant upper limbs, respectively.

Conclusion

Young competitive swimmers seem able to transfer approximately 44% of their maximum strength from land to the water during front crawl actions. The current results provide a first clue about the strength level that young swimmers could apply in water by considering the dry land assessment. Despite both upper limbs eliciting similar strength, the swimming coaches should be aware of the hypothetical muscle imbalances that could impair the force transfer and, therefore, swimming performance.

Santos, C. C., Marinho, D. A., & Costa, M. J. (2022). How much strength the young competitive swimmers are able to transfer from dry land to water? A pilot study. In Dela, F., Piacentini, M.F., Helge, J.W., Lluch, Á., Sáez, E., Blanco, F., Tsolakidis, E., Ruiter, C.J., & Tsolakidis, E. (eds). Book of Abstracts from the 27th Annual Congress of the European College of Sport Science. p. 265. University of Pablo de Olavide. ISBN 978-3-9818414-5-9

Appendix V

The effect of using a parachute on the propulsive force and stroke mechanics during pace-controlled swimming: a case study with an international level swimmer

Biomechanical analysis in swimming has been widely undertaken with propulsion and add-resistance materials. This approach tried to understand how coordination and stroke mechanics were influenced by using such aids. To date, just one study aimed to understand the effect of parachute on the propulsive force at different water flows in a flume (Schnitzler et al., 2011). Thus, the aim of the current study was to analyze the effect of using a parachute on the kinetic and kinematic variables at different swimming velocities. An international female swimmer (age: 18 years-old) was recruited to perform three all-out trials in front-crawl at different swimming velocities (0.80, 1 and 1.20 $m \cdot s^{-1}$). This was done in two different conditions: free-swimming (FS) and swimming with a parachute (SP). The swimming velocity were controlled by a visual light pacer (DigiSwim Pacing System, Digiwest, PT) and the propulsive force (PF, N), was measured with a differential pressure system (Aquanex 4.1, STR, USA) allowing retrieve PF values for the dominant (PF_D) and non-dominant (PF_{ND}) upper-limbs. The Symmetry Index (SyI, %) was calculated as reported elsewhere (Robinson et al., 1987). The stroke frequency (SF, Hz) was assessed with a chrono-frequency meter (FINIS 3x300, Finis Inc., USA) and, therefore, the stroke length (SL, $m \cdot c^{-1}$) and stroke index (SI, $m^2 \cdot c^{-1} \cdot s^{-1}$) were estimated. Swimming with the parachute required higher propulsive forces in both limbs, as the velocity increased (Table 1). The SyI showed a tendency to decrease, as the velocity and propulsive force increased. It seems that when the velocity is near to the maximum (50-m best personal record), a decrease in the deficit of the force applied by both limbs is shown, representing a more comfortable swim pace to use. Only the velocity of 1.20 $m \cdot s^{-1}$ showed a SyI below of 10% (cut-off value), being considered as a symmetric stroke. The SL and SI were lower in the parachute condition since the additional resistance led to a greater effort and SF. The SF presented an incremental increase within the different velocities. Swimming coaches should be aware of the hypothetical significant differences in kinetic and kinematic variables when using a parachute. The lower velocities should be avoided to maintain the integrity of the force applied and to reach a more symmetric motor pattern.

Table 1. Kinetic and kinematic variables at different swimming velocities.

Conditions		Variables					
		PF_D (N)	PF_{ND} (N)	SyI (%)	SF (Hz)	SL ($m \cdot c^{-1}$)	SI ($m^2 \cdot c^{-1} \cdot s^{-1}$)
0.80 ($m \cdot s^{-1}$)	FS	38.02	25.91	37.89	0.41	1.94	1.55
	SP	52.98	42.01	23.10	0.51	1.58	1.26
1.00 ($m \cdot s^{-1}$)	FS	52.42	42.30	21.31	0.55	1.82	1.82
	SP	68.67	60.03	13.43	0.59	1.69	1.69
1.20 ($m \cdot s^{-1}$)	FS	61.81	58.13	6.14	0.60	2.00	2.40
	SP	75.04	67.65	10.36	0.73	1.65	1.98

%, percentage; FS, free-swimming; SP, swimming with a parachute; PF_D, propulsive force of dominant limb; PF_{ND}, propulsive force of non-dominant limb; SyI, Symmetry Index; SF, stroke frequency; SL, stroke length; SI, stroke index; N, Newton; $m \cdot c^{-1}$, meter per cycle; $m \cdot s^{-1}$, meter per second.

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